ALLIS-CHALMERS Electrical REVIEW

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No Excessive Heating

New Rectifier Cooling System Prevents Heat Build-up and Damage

when ac Power Fails

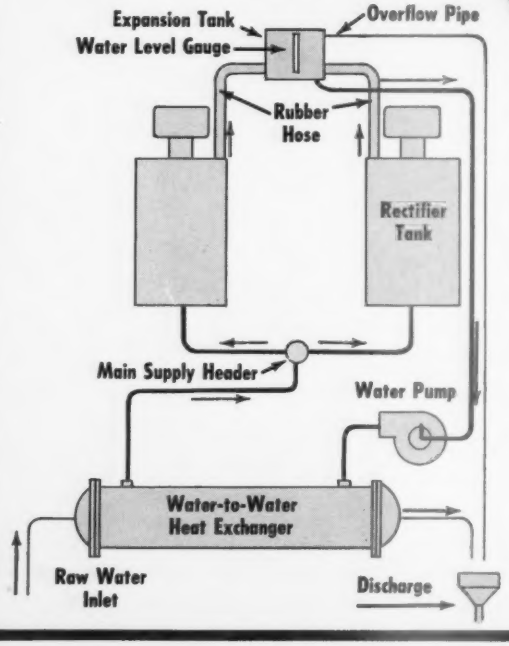
A SAFER, more effective cooling system in the Allis-Chalmers rectifier continues to circulate water *even when an ac power failure stops the water pump.* Heat and steam are dissipated before they can develop to the danger point.

The new system features an expansion tank that extends the full length of the rectifier frame with short vertical connections from each tube. With warm water continuing to flow freely upward, a thermo-siphoning action draws cooler water into the tubes. Build-up of excessive temperatures is prevented. Steam pockets are kept from forming. Subsequent water loss from the recirculating cooling system is minimized.

Successful operation in hundreds of installations is your assurance of the complete reliability of Allis-Chalmers mercury arc rectifiers. Contact your nearby A-C office or write Allis-Chalmers, Industrial Equipment Division, Milwaukee 1, Wis.

How the System Works

Water is normally pumped through the water-to-water heat exchanger to the main supply header from where it circulates through rectifier tubes picking up heat. Hot water flows up through the short connections to expansion tank and back down to suction side of water pump.



Factory-packaged units cut installation time and costs. Sealed tube rectifiers are supplied in completely enclosed or open types. Here is a typical, completely enclosed, 1000-kw, 250-volt rectifier for steel mill service.

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Electrical REVIEW

THE COVER

LOOKING DOWNSTREAM you see new Box Canyon hydroelectric project of Public Utility District No. 1 of Pend Oreille County, near Ione, Washington. In right foreground is main spillway of dam with gates open under flood conditions. Semi-outdoor type powerhouse in left background contains four Kaplan propeller-type hydraulic turbines, each rated 24,500 hp at 100 rpm under 41-ft head.

Allis-Chalmers Staff Photo by Frank E. Hart

Allis-Chalmers

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CONTENTS

Selecting Nuclear Pumps and Motors..... 4
A. F. Erwin

Statistical Quality Control Plus Tabulating Machines Helps Purchaser and Vendor..... 10
William F. Kohl

Curve Fitting..... 14
Thomas R. Hoffmann

Periodic Circuit Breaker Tests Cut Maintenance Costs 20
E. R. Perry

Solve Axial Thrust Problems with Limited End Float Couplings..... 23
E. B. Mills and J. E. Petermann

Three-Phase Power Transformers Gain Popularity... 27
E. G. Ashbaugh

Engineers Discuss Dollar Dynamics..... 28
Stephen M. Hill

Variable Speed Drives Using AC Equipment..... 30
Harlan S. Neuville

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NUCLEAR PUMP, being installed in a high pressure test circuit, will deliver 18,300 gpm at 111 psi and 500 F for a PWR type plant. A 1500-hp drive motor is integral with pump assembly. **(FIGURE 1)**

Selecting NUCLEAR PUMPS and MOTORS

by **A. F. ERWIN**
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Nuclear Pump Section
Centrifugal Pump Dept.
Allis-Chalmers Mfg. Co.

Nuclear power plants require special pumps. Here are the special factors influencing pump selection

TODAY SEVERAL TYPES of nuclear power plants have been developed and are now in operation. Among these are the Pressurized Water Reactor, Boiling Water Reactor, Homogeneous Reactor, and Liquid-Metal-Cooled Reactor. The pumps used in reactors for these plants must be able to carry radioactive materials safely at the required high temperatures and pressures. Selecting main coolant pumps, drives, and controls for nuclear plants includes most of the factors affecting conventional pump installations. In addition special factors are involved in all nuclear plants and their problems considered individually.

The Pressurized Water Reactor type plant (PWR) flow diagram is shown in Figure 2. Its development was aided by the well established technology of handling high pressure hot water (2000 psi, 500 F), and, as expected, no insuperable corrosion problems were encountered. The success of the plant has established this type as standard for the current nuclear ship power plant program and for the Package Power Reactor program. The 60-Mw Shippingport plant now being installed for the Duquesne Light Company is of this type, as is the 236-Mw central station power plant being manufactured for Consolidated Edison Company's Indian Point, New York, station. Pressurized Water Reactor power plants are also planned for the Dominican Republic, Belgium, Italy, and Brazil.

Main coolant pump requirements for these plants are almost identical to those for boiler recirculating pumps in high pressure forced circulation boilers. These boilers have until recently used buffer seal pumps with cold water injected into the seal at high pressure to permit taking a pressure drop through the seal labyrinths without flashing steam, and are provided with a mechanical seal to contain leak-off for return to the system. The buffer seal has not been entirely satisfactory in the higher pressure conventional plants because of uncontrolled cold water inleakage to the system, with consequent reduction in thermal efficiency, boiler feed control problems, high maintenance cost, and somewhat unpredictable dependability.

Pressurized water reactor pumps chosen for reduced leakage

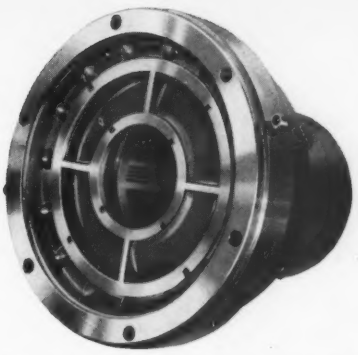
Several central stations have installed hermetically sealed (canned motor) pump units recently for trial as boiler recirculators under these conditions, although their initial cost is considerably higher than that of buffer seal pumps. For similar reasons, including the desirability of complete sealing against leaks and maximum dependability in submarines and other ships, canned motor pumps have been selected as standard. They have also been specified for the Shippingport plant, shown in Figure 1, and Indian Point central station plant. However, buffer seal pumps are being considered for marine and other use. The development of better buffer seals, with reduced leakage rates and improved dependability, could make first cost the determining factor in future Pressurized Water Reactor type pump selection. Although the primary cooling water does not normally become highly radioactive in these plants, and the radiation intensity falls off to tolerable levels for maintenance in a short time after shutdown, the completely leakproof design is favored because a possible rupture of a fuel element will contaminate the water, making it highly radioactive. This possibility also makes it essential to provide connections for complete flushing and draining for decontamination of the entire unit.

Other factors in Pressurized Water Reactor type pumps and motors are overall efficiency, type of bearing (graphite versus hydrostatic), and type of electrical insulation (mica-glass-silicone versus silicone-rubber insulation). Design features necessary for maximum ruggedness and dependability are essential. A typical fluid piston (hydrostatic) radial and thrust bearing, which can use corrosion-resistant materials suitable for high temperature, is shown in Figure 3. Valves are avoided in primary coolant flow control in reactor plants wherever possible because of their inaccessibility for maintenance and need for hermetic sealing. In addition the probability of sliding surfaces sticking and causing operating failure, and their high cost, make such valves undesirable. The ideal flow control for the reactor would have wide range and stepless controllability capable of being precisely held at any selected point, from full flow down to just a few percent of rating. In early units the variable flow range was limited to a minimum flow of 20 or 25 percent. Pump speed was controlled by variable frequency control from full flow down to 50 percent flow, with a single point of operation at 25 percent flow, by using a separate small 15-cycle generator for standby cooling condition. The trend is toward eliminating the stepless control entirely and utilizing two-speed motors to provide for a reduced flow capability at one-half, one-third, or one-quarter speed.

Multiple pump installations in parallel provide variations in flow by cutting out one or more units, using check valves in the discharge of each pump to control recirculating flow. Condensate pumps and boiler feed pumps for Pressurized Water Reactor plants are in the non-radioactive secondary water circuit, and may therefore be of conventional design, utilizing standard pumps, motors, and control.

Forced circulation raises reactor output

The original 5-Mw Experimental Boiling Water Reactor (EBWR) plant at Argonne National Laboratory, shown in Figure 4, employs thermal head to circulate coolant in the reactor. The Arbor Project Reactor of Argonne National Laboratory will use forced circulation to increase output. The 180-Mw Commonwealth Edison and Nuclear Power Group plant at Dresden, Illinois, will be a dual cycle boiling water reactor with forced circulation through a secondary steam generator, using canned motor pumps. The 66-Mw (gross electric) Northern States Power Company plant will be a Controlled Recirculation Boiling Reactor (CRBR), using multiple forced circulation pumps of a type to be

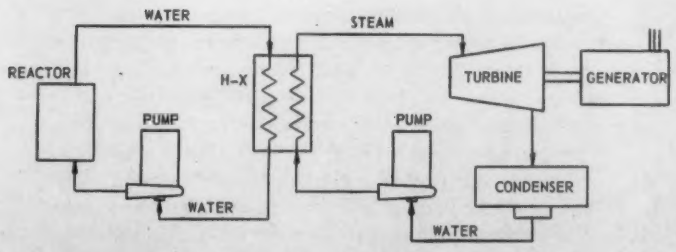


THE BEARING shown above is operated in the high temperature fluids found in nuclear power plants. Materials used in its construction resist corrosion and wear for years of service. **(FIGURE 3)**

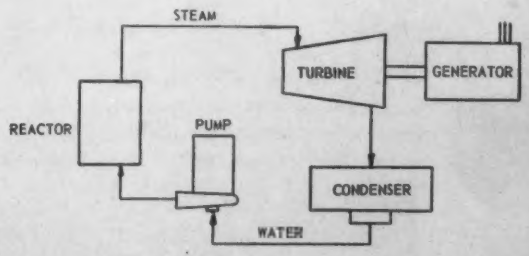
selected. Pressure levels are generally lower in boiling reactors than in Pressurized Water Reactor types, ranging from 600 to 1200 psi at corresponding saturation temperatures. This system requires the main coolant pumps to handle water near its boiling point, usually at relatively low head, with the suction head limited to the gravity head above the pump plus whatever sub-cooling can be provided by introducing the colder boiler feed water into the suction of the circulating pump, and may require double-suction pumps or multiple pump installations to avoid severe cavitation conditions. Cavitation is particularly undesirable in these circulating pumps because the rate of reaction and output of the reactor are immediately affected by changes in coolant flow. However, pumps can be carefully designed for these extreme conditions. Troublesome reactor operation because of the intermittent coolant flow, resulting from cavitation, can be avoided.

Control of circulating flow by pump speed control is highly desirable to avoid dependence on remote-controlled hermetically sealed valves under these difficult conditions. The variable flow requirement makes it necessary for the pump to operate from time to time at speeds other than at its best conditions, with increased suction head requirements necessary during these periods. The lower system pressure, preference for double suction, and variable speed requirements all favor the selection of mechanically sealed pumps. The buffer seal type appears suitable, or an externally enclosed motor drive can be used, operating in an inert-gas atmosphere above the reactor liquid level where some gas in solution in the coolant can be tolerated.

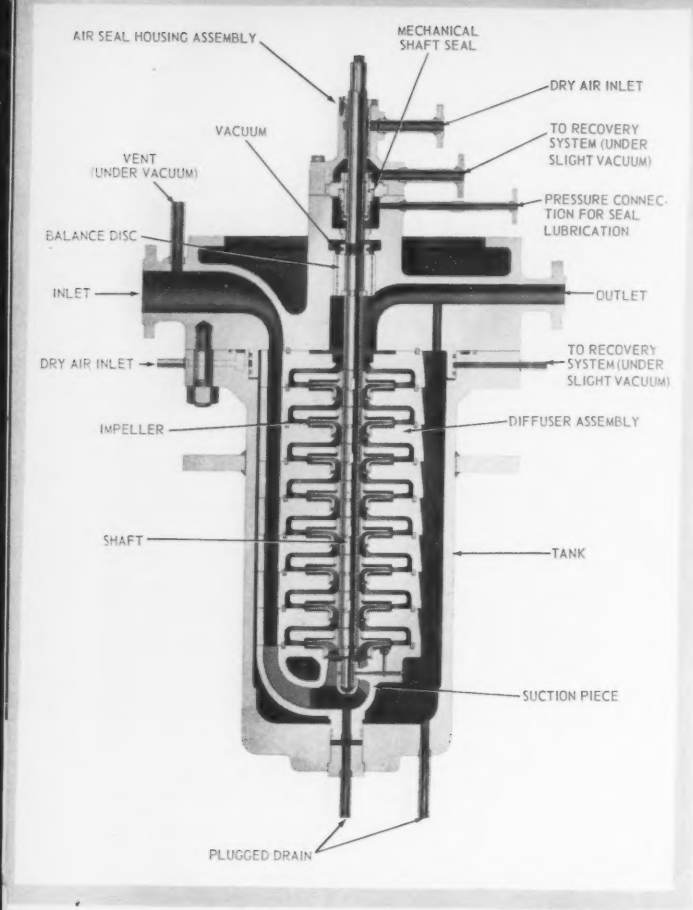
For condensate and boiler feed pump service, a combined pump unit, shown in Figure 5, was selected in the Argonne Boiling Water Reactor plant so that only one



PRESSURIZED WATER REACTOR diagram shows the principal elements. The secondary circuit is non-radioactive. **(FIGURE 2)**



BOILING WATER REACTOR eliminates the heat exchanger and the secondary circuit auxiliaries of the PWR circuit. **(FIGURE 4)**



REACTOR FEED-WATER PUMPS combine function of both condensate and boiler feed pumps in conventional plant. This construction reduces leakage by limiting shaft seals to one. Motor thrust bearing carries total vertical thrust. Radial thrust at lower end of shaft is handled by fluid piston type water-lubricated bearing. **(FIG. 5)**

shaft seal was required. This seal provided for controlled leak-off to a recovery system, with dehydrated air supplied to the seal and flanges to avoid contamination with atmospheric moisture when heavy water is used as a primary coolant.

A bypass purification circuit will usually be specified for removal of solids from the coolant by filtration. For the Boiling Water Reactor a hermetic pump, shown in Figure 6, has been installed, designed for 50 gpm, 95-ft head, and 1000 psi system pressure. This purification method results in very low radiation intensity in the primary water, so that equipment in the primary circuit outside of the reactor shielding can be directly inspected or adjusted while in operation if necessary. However, the possibility of severe radiation occurring, such as would exist after failure of a fuel element enclosure, may be the deciding factor in favor of hermetic pumps in future installations.

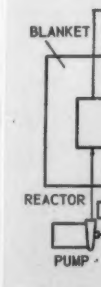
Homogeneous reactors use aqueous solutions

In the homogeneous reactor developed by Oak Ridge National Laboratories, shown schematically in Figure 7, the fuel is in solution in normal water or heavy water, which acts also as both moderator and coolant for the reactor. As in the Pressurized Water Reactor and Boiling Water Reactor types, a high pressure level is essential to secure reasonably high temperature of the water in the reactor. Homogeneous Reactor Experiment No. 1 (HRE-1), 1000 thermal kw, was operated at 1000 psi and used a 150-gpm canned motor fuel solution circulating pump. Homogeneous Reactor Experiment No. 2 (HRE), 5000 thermal kw, operates at 2000 psi, using a 400-gpm canned motor fuel circulating pump. For the third step, designated HRP, a 50-Mw thorium breeder type, a 4000-gpm, 200-ft head canned motor fuel circulating pump is specified. A 150-Mw plant, the Pennsylvania Advanced Reactor Project (PAR), of the aqueous homogeneous reactor type, has been contracted for by Pennsylvania Power and Light Company. This plant is expected to use four 8000-gpm, 150-ft head canned pumps. The Wolverine Electric Cooperative has also selected an aqueous homogeneous reactor, rated 10 Mw, using uranyl sulphate dissolved in heavy water as fuel, moderator, and coolant. Canned motor pumps are specified for this plant, which is one of the AEC power demonstration program plants. A somewhat different homogeneous reactor, the Los Alamos Power Reactor Experiment (LAPRE-1), developed by Los Alamos Scientific Laboratory, is based on recirculating the fuel solution within the reactor vessel under supercritical temperature and pressure conditions. The pump impeller for a small-scale test of this system projects into the reactor vessel, which contains baffles acting as the pump casing. This gold-plated impeller and its canned drive motor rotor are shown in Figure 9.

Corrosive fuels require special pumps

The most important special factor affecting pump selection for aqueous homogeneous reactors is the highly corrosive nature of the fuel solutions at high temperatures. Corrosion is most severe in the parts exposed to high liquid velocities, which may limit materials for such parts to titanium, tantalum, tungsten or even gold and platinum, in solid, clad, or plated form. Variations of the homogeneous reactor incorporating breeding blankets for converting materials such as natural uranium, spent uranium or thorium to fissionable material are under development. Similar corrosive, high temperature, and high pressure conditions will be encountered except when these materials are to be circulated in the form of insoluble suspensions or slurries. Corrosion will be greatly reduced when slurries are circulated, but they will cause an abrasion problem. Tests on pumping thorium slurry of micron size sharp particles showed a serious wear rate for the first several hundred hours, after which the particles were reduced to submicron size rounded particles and the rate of wear decreased to tolerable levels.

The efficiency of reactors is increased by use of heavy water as a coolant, moderator, and fuel carrier, because it captures less neutrons than normal water absorbs. However, with either coolant the fuel solution in all parts of the primary circuit of homogeneous reactors is highly radioactive, including delayed neutron radiation. The use of buffer seal pumps for homogeneous reactor fuel circulation has been considered for cost reduction, but the highly corrosive conditions, the need for complete sealing against leaks, and the inaccessibility for maintenance due to radioactivity have favored the selection of the canned motor



THIS CANNED ROTOR PUMP, after it has been installed in a Boiling Water Reactor plant, serves to circulate a portion of the reactor coolant through a bypass purification system. **(FIGURE 6)**

pump. The intense and long-lasting radioactivity of the pump materials after being exposed to neutron radiation may require pump units designated for remote-controlled removal and replacement.

Control of homogeneous reactors is claimed to be almost automatic. The demand for increased power causes a pressure drop in the steam generator which cools the primary fluid, causing increased density in the reactor, thus increasing the critical mass and output. Similarly, decreased demand takes less heat, increasing the fuel solution temperature, which decreases the reactor output. The pump flow can therefore be at a uniform rate except during starting up, when a low flow is desired for a short time until the system is warmed up. This flow has been secured in the Homogeneous Reactor Experiments by running the circulating pump backward for a five-minute warmup period. This method may be practical for later installations if the specific speed selected is low enough to permit the unit to pump in the same direction with reversed rotation. Control for the circulating pumps is therefore expected to be conventional starting and protection equipment, with the alternate possibility of two-speed motor control or reversing control for the short-time low flow condition.

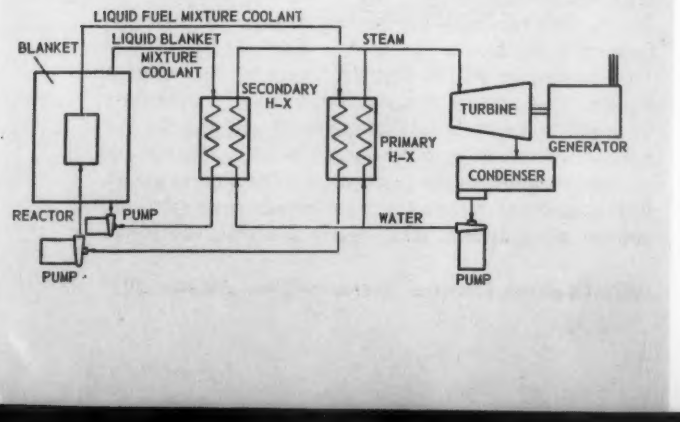
Liquid metal coolants show promise

A typical liquid metal reactor flow diagram is shown in Figure 8. For the first liquid-metal-cooled ship reactor, designated Ship Intermediate Reactor (SIR), an intensive pump development program was carried out, resulting in the development of electromagnetic pumps that have proved satisfactory in several variations. Canned motor centrifugal pumps and several special liquid metal seals for mechanical pumps were also developed. Many difficulties in the circulation and containment of the preferred liquid metals, such as the hazards of self-ignition upon exposure to atmosphere, the creation of explosive gases upon contact with water, solidification upon cooling, plugging from oxygen contamination, mass transfer of materials, self-welding of rubbing parts and severe thermal shock due to high heat transfer rates have been overcome. In spite of the foregoing difficulties, the use of liquid metals as reactor coolants presents such great advantages that many reactor systems are being developed to utilize them. These advantages include high heat transfer rates, low vapor pressures at high temperatures, low pumping power for the lighter metals such as sodium, potassium, and lithium, low absorption of neutrons, and relatively low corrosiveness with preferred materials of construction.

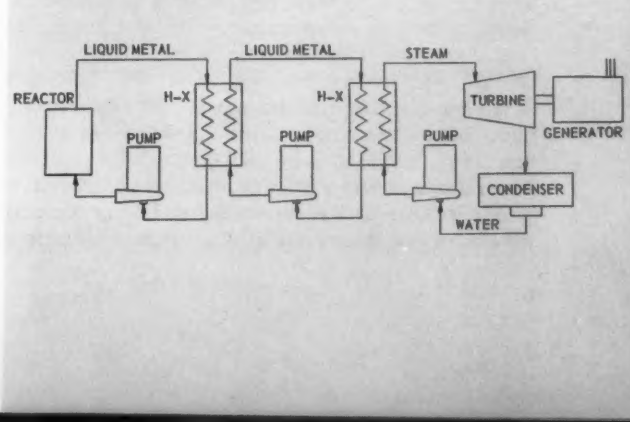
Argonne National Laboratory has developed and tested the first Experimental Breeder Reactor (EBR I) and is currently completing prototype tests for the 20-Mw EBR II plant. A prototype pump installed in the test circuit for EBR II is shown in Figure 10. This unit is essentially a conventional centrifugal pump. It has a sump tank above the pump in which the liquid metal level is controlled. The tank is connected to a shaft enclosure and to the motor housing which maintain an inert-gas atmosphere above the liquid, eliminating the need for shaft seals. A long shaft extension is desirable in high temperature liquid pumps, in order to provide an adequate temperature gradient in the shaft, so that acceptable temperatures can be maintained at the motor bearings and windings. This long shaft extension is made possible by utilizing the previously described fluid piston bearing principle to replace one or both of the pump wearing rings with steady bearings, pressurized by the high temperature fluid. This bearing is shown in Figure 11.

The first Experimental Breeder Reactor used sodium-potassium alloy, *NaK*, as a coolant in both primary and secondary circuits, while EBR II will use sodium in both circuits, with pumps rated approximately 6000 gpm at 160-ft head, 700 F. The Power Reactor Development Company's 300 thermal Mw Enrico Fermi plant will also

HOMOGENEOUS REACTOR diagram shows main elements including reactor and blanket circuit heat exchangers. Pumps are similar to those in PWR plants, except they must circulate corrosive or abrasive fluids at high operating temperatures desired. **(FIGURE 7)**



LIQUID-METAL-COOLED REACTOR circulates the liquid metal in two circuits, which are separated from the water system by two heat exchangers. Being non-radioactive, the water system permits using customary seals for the turbine and its auxiliaries. **(FIGURE 8)**



PUMP IMPELLER and drive rotor recirculate fuel solution. The gold-plated impeller effectively resists corrosion. **(FIGURE 9)**

be a fast breeder reactor, liquid-metal-cooled type, using three 11,800-gpm, 310-ft head sodium pumps in the primary circuit and three 11,800-gpm, 60-ft head sodium pumps in the secondary circuit. The term "fast" refers to neutron velocities. Reactors can be classified into three types according to their neutron velocity (or energy): fast, intermediate, and thermal. Two intermediate velocity sodium-cooled reactors have been built, using beryllium to moderate or reduce the neutron energy to intermediate levels. For both of these plants alternating-current electromagnetic pumps were selected because of their more advanced development at the time.

Because of their inherent nature, fast breeder reactors must be designed to prevent loss of coolant, which could result in meltdown of the core into a supercritical mass. These reactors must also be designed to prevent any moderator-type materials, such as oil or water, from entering the system, as these could increase the reactivity beyond safe limits. For these reasons the primary coolant pumps and piping are usually contained within secondary enclosures so that a leak should not cause excessive loss of sodium. The system design also preferably provides sufficient natural convection circulation for removal of the decay heat that is emitted after shutdown, to prevent melting of the core in the event of loss of power for the pumps.

Research investigates fast reactors

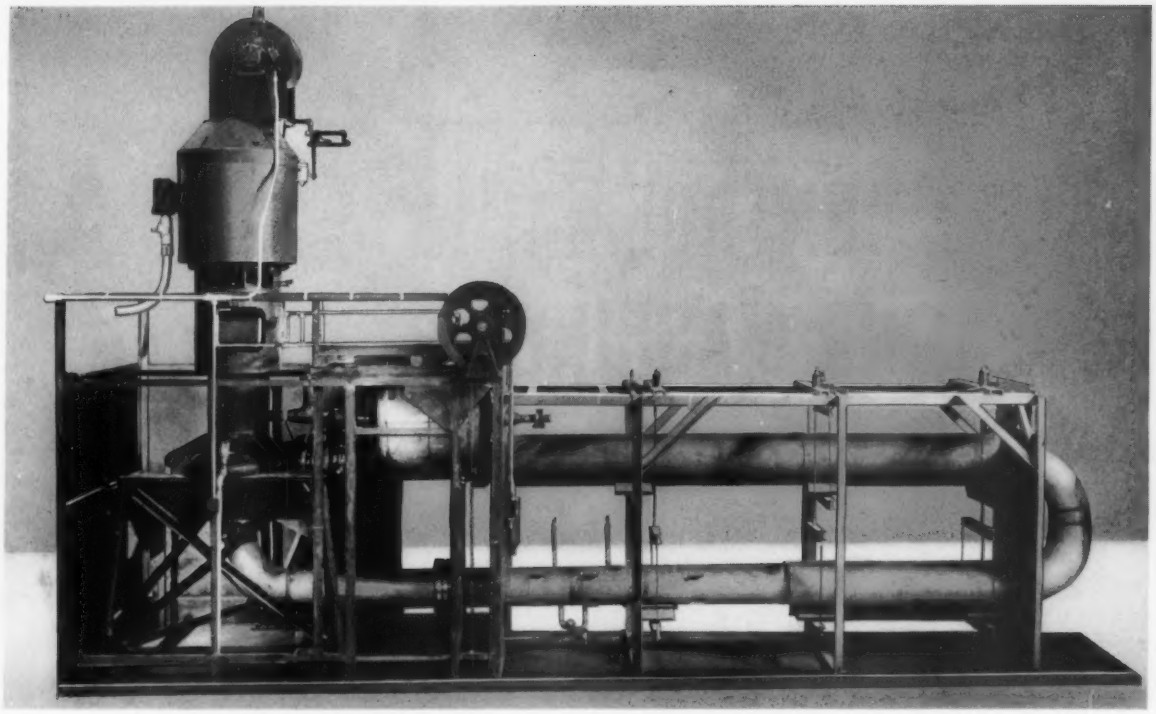
Research for future fast reactors is being carried out in two configurations by Argonne National Laboratory, in their zero power reactors ZPR III at Arco, Idaho, and ZPR V, a combined fast and thermal neutron reactor. A three-phase program is planned at Los Alamos Scientific Laboratory, the first step of which is the 1000-kw Los Alamos Molten Plutonium Reactor Experiment (LAMPRE-1). This unit will use molten plutonium as the reactor fuel, permitting continuous removal of fission products. Sodium at 1000 F is the coolant. Pumps for this reactor have not yet been selected.

Other light liquid-metal-cooled reactors that have been declassified up to this time include the sodium-graphite reactor experiment (SRE), a 7.5-Mw developmental plant providing power to Southern California Edison. This plant is the prototype for a 75-Mw plant proposed by Consumers' Public Power District, Nebraska. The 7.5-Mw SRE plant uses conventional centrifugal pumps with a frozen sodium shaft seal which is confined in an inert-gas enclosure by mechanical seals. Other types of pumps are under consideration for the 75-Mw Nebraska plant, but these have not as yet been selected.

An ingenious combination of the molten fuel, solid moderator, and liquid metal coolant features is found in the Liquid Metal Fueled Reactor Experiment (LMFRE), developed by Brookhaven National Laboratory. This reactor system is based on metallic uranium dissolved in liquid bismuth acting both as the fuel and primary coolant. The liquid is pumped through channels in a block of graphite where this moderator causes the fission reaction to take place, and then through a heat exchanger which transfers the heat to the secondary sodium circuit. Around the reactor core is a secondary container or "blanket" in which a bismuth-thorium slurry is circulated to breed new fuel. Fuel and blanket fluids are circulated with molten salt through a continuous process for removal of fission products. Thus there are three coolant pump applications and a molten or fused salt pump application in the Liquid Metal Fueled Reactor.

A gas atmosphere can be maintained over each of these fluids, permitting consideration of mechanical seals. Moreover, the high radiation level in the two bismuth circuits and the fused salt circuit, the high temperature level of 1000 F or more in all four circuits, and the high melting point of the bismuth and salt create difficulties for the canned motor pump and electromagnetic pump designers in protecting the electrical insulation from the high temperatures required for operation, as well as for melting or maintaining the molten condition in starting or standby condition.

When canned motor pumps are used for low melting point metals, such as sodium without fuel in solution, it is possible for liquid sodium to surround the motor rotor and lubricate the bearings by maintaining the liquid in that area at relatively low temperature (250 F). Since oxides are precipitated in this cool zone, a filtration bypass circuit is required to avoid buildup of these solids. However, the bismuth fuel and slurry must be maintained at a temperature well above its 520 F melting point, and the fused salts at similar or higher temperature levels, to avoid freezing at the coldest zones. It is also desirable to avoid mass transfer of fuel to the cold zones by operating all parts of these circuits at as nearly uniform temperatures as possible. An additional complication exists in the bismuth circuits because a very active poison, polonium, is produced when bismuth is subjected to neutron radiation. The selection of pumps for these circuits must take into account all of these factors. Mechanical seals should not



HERMETICALLY SEALED, motor-driven, liquid metal centrifugal pump on 5000 hr test in ANL test loop. This pump has capacity of 5000 gpm at 100 ft head of high temperature sodium. **(FIG. 10)**

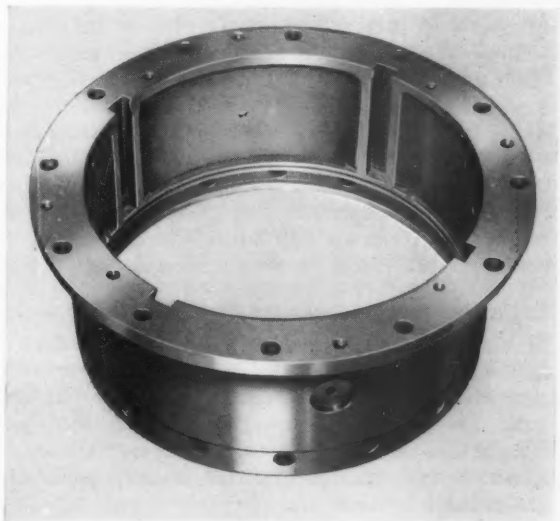
be depended upon to maintain the inert-gas atmosphere for such service. Seal lubrication is difficult or impossible because of the temperature and contamination conditions under which the unpredictable service life of mechanical seals could cause extensive shutdowns and highly hazardous conditions for personnel.

Two types of hermetically sealed pumps have been developed to maintain an inert-gas atmosphere above high temperature liquid metals. One type is essentially a canned motor unit with the stator can containing a gas in the motor rotor space. In this unit the liquid level is maintained in a narrow annulus around the shaft between the pump and the motor rotor. The other type utilizes the external enclosure of a totally enclosed fan-cooled motor to contain the inert gas above the liquid, which is held at the preferred level in a sump tank above the pump casing. The hermetically sealed pump unit described above is of the second type. Its design permits the application of developed and tested pumps and motors to assure the selection of the most suitable unit for each specific application without duplicating the basic development and tooling involved.

Control of the Liquid Metal Fueled Reactor will probably require variable flow without use of throttle valves in the bismuth-fuel circuit. Variable flow can be accomplished by providing a variable-frequency power supply for the required range. A suitable power supply may be comprised of an ac motor driving an ac generator through a suitable variable-speed device such as an eddy-current clutch. For wider speed range, a frequency converter with auxiliary dc motor drive may be used. The control of the pumps in the other three circuits is expected to be conventional, with a possible requirement for two-speed motor drives. Canned motor, electromagnetic, buffer sealed, and hermetically sealed pumps, with suitable drives, power supplies and controls for all current reactor plants are available.

Engineers and research scientists are continually working on the development of pumps for nuclear reactors. Pump development is keeping pace with the growing variety of nuclear power facilities.

FLUID PISTON bearing is for pump shown in Figure 10. Bearing pressure is maintained by high temperature fluid. **(FIGURE 11)**



STATISTICAL QUALITY CONTROL PLUS TABULATING MACHINES

Helps Purchaser and Vendor

PUNCHED CARD machines print summary reports for inspection, purchasing, and design departments.

by **WILLIAM F. KOHL**
Inspection Department
Allis-Chalmers Mfg. Co.

Tabulating equipment can help you control your material quality when buying, supplying, or engineering products.

INDUSTRY HAS LONG TRIED to achieve control over the quality of purchased material and many approaches have been tried, ranging from no inspection with blind faith to 100% inspection with high cost. During the past three years, however, a system of Statistical Quality Control (SQC) plus tabulating equipment has been developed to control incoming quality simply and economically.

This new combination of Statistical Quality Control and tabulating equipment utilizes definite inspection procedures which outline the desired quality levels and employs economical sampling plans capable of insuring the desired levels of quality. Most important of all, it provides, through the use of tabulating equipment, clear-cut factual data which will help to improve the quality of the purchased products and will help develop sources which can be relied upon to supply material of consistently good quality.

Engineers also receive quality reports

In this system, as seen in Figure 1, inspection follows a fairly standard procedure in the acceptance or rejection of material. Sampling tables, based on Military Standard 105A, are used, and the usual report is written when material is rejected. Occasionally it may be necessary to screen or repair defective material urgently needed by production.

All of this procedure is familiar to receiving inspection organizations; the same thing happens every day in thousands of receiving departments. However, this Statistical Quality Control-Tabulating system goes beyond the usual receiving inspection and records and analyzes the results of the inspection. It makes possible reports on vendor quality for use by the Purchasing Department in helping vendors to improve their quality, and for use by the Engineering Department in improving the design of products.

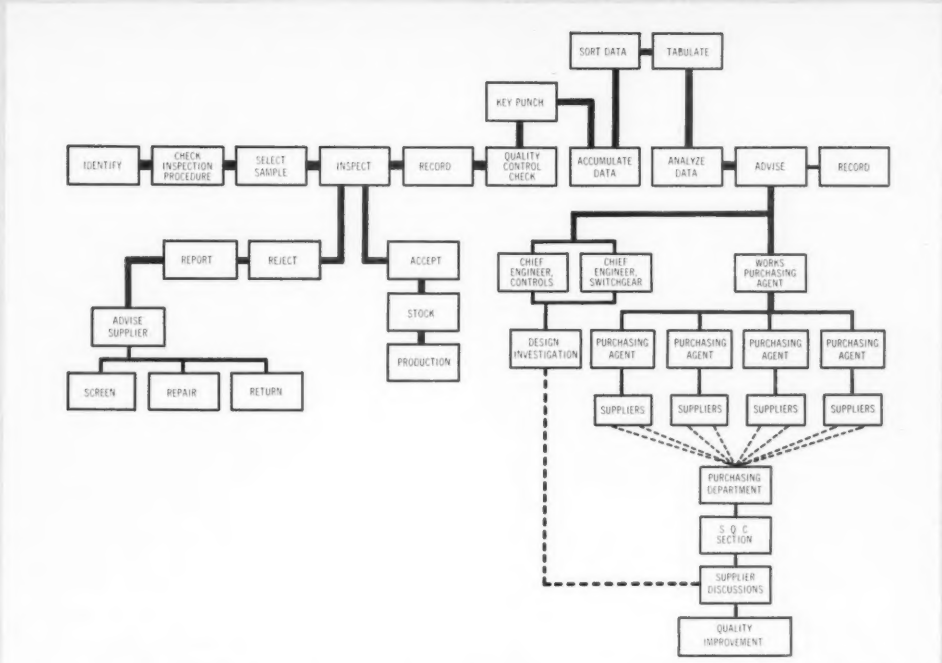
The entire system is quite easy to administer and benefits both the purchaser and the vendor. In preparing for inspection, the inspector checks the packing slip and purchase order and obtains whatever drawings are needed from the file. Next he refers to the Inspection Instruction Card, shown in Figure 2, which tells him the Acceptable Quality Level (AQL), gages required for inspection, inspection details, and special tests where necessary.

Then the inspector refers to the sampling table, Figure 3, under the Acceptable Quality Level specified and selects the sample as indicated. The inspector proceeds with his inspection, basing his acceptance or rejection on the sampling table and nature of the defect as noted on the Inspection Instruction Card. In the event of rejection, a rejection report is filled out.

Having obtained the vendor code number from the Vendor Code Book, which is indexed both alphabetically and numerically for easy reference, the inspector records the results of his inspection on the Vendor Quality Record Sheet, Figure 4. With the recording of this information the inspector's part of the operation is complete.

The simplicity of the system at this point is self-evident. It requires a minimum of instruction to inaugurate and a

(Continued on p. 12)



FLOW DIAGRAM illustrates possible paths that purchased material may take and how reports may move to various departments and result in improved quality. **(FIG. 1)**

TERMS AND DEFINITIONS

Statistical Quality Control (frequently labeled SQC) is based upon the theories of statistics and probability and is a technique for establishing and controlling quality. Problems are approached from the viewpoint that all things vary, predictably.

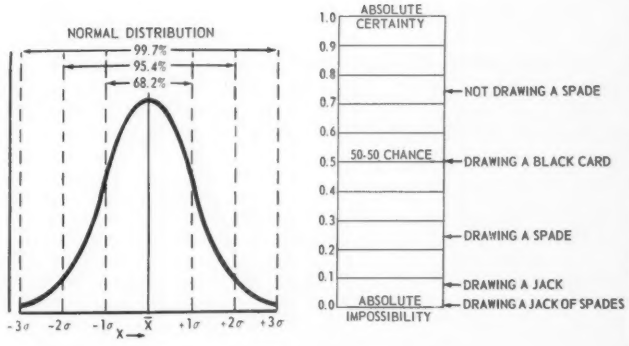
Under normal conditions this variability leads to a symmetric frequency distribution of measured quantities about a central value. Graphically this is a bell-shaped curve showing most of the values near the central value and a few far from it. A measure of how closely the individual values cluster about the central value is the root-mean-square deviation, sigma (σ).

$$\sigma = \sqrt{\frac{(\bar{x} - x_1)^2 + (\bar{x} - x_2)^2 + \ldots + (\bar{x} - x_n)^2}{n}}$$

$\bar{x}$ equals the central value, x_n equals the individual values, and n equals the total number of values. Mathematically it can be shown that 99.73% of the measurements will lie between $+3\sigma$'s and -3σ's.

Probability theory places all occurrences on a scale varying between 0 (absolute impossibility) and 1 (absolute certainty). For example, the probability of drawing a black card from a normal 52 card bridge deck is .500; the probability of drawing a spade is .250; the probability of drawing a jack is .077; and the probability of drawing the jack of spades is approximately .0192. Thus it can be seen that the probability that a value will be more than 3σ's from the mean, as a result of chance causes only, is .0027.

Using such principles, it is possible to develop several unique methods for controlling quality because variations



larger than three sigmas are most likely (9973 times out of 10,000) due to assignable causes.

By sampling, which is drawing a representative group from a lot, it is possible to get a picture of the entire lot's characteristics. Sampling tables, like Military Standard 105A, are systematic plans developed to give desired levels of quality with varying degrees of certainty. This level of quality wanted is labeled the Acceptable Quality Level (AQL) and is the fraction of defective parts in a lot that can be tolerated without seriously affecting further processing operations. With sampling it is possible to attain this Acceptable Quality Level with a predetermined risk, usually 10 - 1, that no lots will be accepted which are worse than this.

Other techniques of statistics and Statistical Quality Control facilitate the setting of tolerances, the controlling of in-process materials and operations, and the designing of products.

PART NUMBER 14-219-055-001
DESCRIPTION Center Element
CLASSIFICATION Critical
ACCEPTABLE QUALITY LEVEL (AQL) 1%
DEGREE OF INSPECTION Normal

INSPECTION INSTRUCTION CARD
QUALITY CONTROL
Movable Contact Carrier
REMARKS for Auxiliary Relay

SEQUENCE	CHARACTERISTIC TO INSPECT	MAJ	MIN	INSTRUMENT OR GAGE
1.	Height of center section - .498"/.505"	x		TEK-12322
2.	Width and centering of element, and alignment of nubs on both sides.	x		TEK-12322
3.	Size of nubs - .120"/.125" to .135"/.140" Check .054"/.058" dimension. (.0535" allowable if less than 1% - info for inspection only.)	x		TEK-12322 Optical Comparator
4.		x		
5.	All fractional dimensions.	x		
6.	Cracks in plastic not acceptable.	x		Visual
7.	Check for blemishes or chips in plastic.		x	Visual

ALLIS-CHALMERS MFG. CO. 14-219-055-001 Center Element 4032

INSPECTION INSTRUCTION CARDS show the acceptable quality levels and how to inspect to maintain them. **(FIGURE 2)**

DOUBLE* SAMPLING PLAN - NORMAL INSPECTION
(Based on MIL-STD-105A)

LOT SIZE	DOUBLE SAMPLING: SAMPLE	SAMPLE SIZE	TOTAL SAMPLE SIZE	ACCEPTABLE QUALITY LEVEL (AQL): 2.50 NON-CRITICAL AC	RE	1.00 CRITICAL AC	RE	0.25 VERY CRITICAL AC	RE	SINGLE SAMPLING: SAMPLE SIZE
41 - 110	- - - -	- - -	- - -	⇩		0	1			15
111 - 180	FIRST	15		0	3	⇧				- - -
	SECOND	30	45	2	3					
181 - 300	FIRST	25		1	4	⇩		⇩		- - -
	SECOND	50	75	3	4					
301 - 500	FIRST	35		1	5	0	3	0	1	50
	SECOND	70	105	4	5	2	3			
501 - 800	FIRST	50		2	6	1	4	⇧		- - -
	SECOND	100	150	6	7	3	4			
801 - 1300	FIRST	75		3	7	1	6	⇩		
	SECOND	150	225	6	8	3	6			
1301 - 3200	FIRST	100		5	9	2	6	0	3	
	SECOND	200	300	12	13	5	6	2	3	
3201 - 8000	FIRST	150		7	11	3	8	1	3	
	SECOND	300	450	18	19	7	8	2	3	
8000 and up	FIRST	200		9	13	4	10	1	6	
	SECOND	400	600	24	25	9	10	5	6	

*For Lot Size and AQL to the left of double line, use double sampling. To the right of double line use single sampling.
⇩ Use sampling plan (sample size, acceptance and rejection numbers) below arrow.
⇧ Use sampling plan (sample size, acceptance and rejection numbers) above arrow.

ALLIS-CHALMERS MFG. COMPANY — SQC SECTION, HARLEY WORKS INSPECTION DEPT.

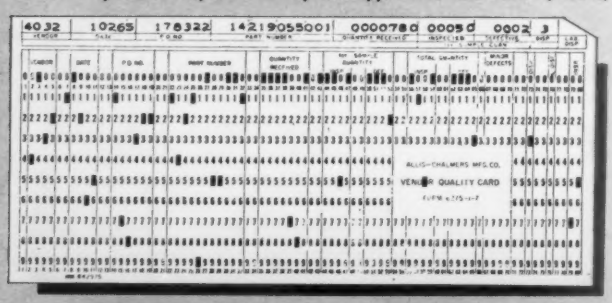
SAMPLING TABLES indicate the sample size and whether to accept, reject, or examine additional quantities. **(FIGURE 3)**

IBM VENDOR QUALITY RECORD
MID-12 908

VENDOR CODE	DATE	PURCHASE ORDER NUMBER	PART NUMBER	LOT SIZE	FIRST SAMPLE SIZE	FIRST SAMPLE DEFECTS	TOTAL SAMPLE SIZE	TOTAL SAMPLE DEFECTS	MINOR DEF	INSP DISP	LAB DISP	INSP CODE
9022	7/18/5	184510	18-681 664 013	24	15	1	24	3		3		46
1002	7/18/5	156530	14 182 111- 501	2	2	0			2	1		70
6018	7/18/5	147778	14 117- 577 001	100	25	0				1		70
1002	7/18/5	149732	14-182 029-501	96	15	0				1		70
1002	7/18/5	166512	14 182 125 501	4	4	0				1		70
6021	7/18/5	147889	14-222-693-001	939	25	25				2		6
5013	10/25/5	156574	42442	20	15	0				1		6
9046	7/18/5	139104	14-129-785 001	648	50	0				1		75
6005	10/25/5	156601	14-119-636 001	250	35	0						75
9056	7/18/5	137634	67828	3000	100	0				1		46
2005	7/18/5	137446	14 125-928 001	200	25	0				1		46
2005	7/18/5	137441	14 125-928 002	200	25	0				1		46
3013	7/18/5	154911	14 108 117 001	2700	150	1				1		70

ALLIS-CHALMERS MFG. COMPANY — STATISTICAL QUALITY CONTROL SECTION HARLEY WORKS INSPECTION DEPARTMENT

VENDOR QUALITY RECORDS are filled out by the receiving department inspector. A shipment appears on each line. **(FIG. 4)**



TABULATING CARDS are punched for each of the entries on the Vendor Quality Record and gathered for a month. **(FIG. 5)**

(Continued from p. 10)

minimum of policing. The forms, kept in pad form and numbered to protect against loss, are centrally located for convenience. Entries can be made in any order, but complete accuracy of the entries must be maintained. Any number of vendors may appear on a sheet.

Periodic tabulations are made

Once each week the sheets are delivered to the tabulating section where the information is entered on keypunch cards — one for each entry. These are referred to as Vendor Quality Cards (Figure 5). After the cards for the week have been punched, they are returned to the Quality Control Section for storage and reference until a summary tabulation is run.

As all Vendor Quality Cards carry a vendor code number, it is necessary to have a Title Card for each vendor. This title card spells out the vendor's name as indicated by the code number so that tabulated data is properly identified. Title cards for the new vendors are punched each month.

Prior to running the summary tabulation, a check is made to determine that all Vendor Quality Cards for the past month are on file. These cards, together with title and summary cards on file, are returned to the tabulating section at the close of each month. The month's quality cards are run through sorting machines to arrange the cards in part number order and then in vendor code number order. After the cards have been sorted in this manner, the summary cards and title cards for the month's active items are sorted out and grouped with the quality cards. This group of cards is then fed into the tabulating machine and the final tabulation run off.

Known as the Vendor Quality Control Tabulation, the form shown in Figure 6 is the end result of all that has gone before. It provides a record of the quality of all items received during the month for which it is run and furnishes the quality information on those parts for the entire year.

The Vendor Quality Control Tabulation consists of one or more sheets, in triplicate, for each vendor. At the top of the sheet appears the vendor's name, the month and the year. In the body of the tabulation is summarized all of the inspection information on each part received. At the bottom appears the total of all shipments to date.

Quality control group analyzes tabulation

Summary Cards, Figure 7, are utilized to retain previous data so that a continuing record for the year may be carried forward to each tabulation. They are similar to the Vendor Quality Card, except they are dated as of the last day of each month and represent all data on a given part and vendor up to and including the recorded date. New Summary Cards are punched automatically at the completion of each tabulation and the previous month's cards are destroyed.

But with all this, it must be kept in mind that no amount of data, however accurate and comprehensive, is of value unless it is analyzed and acted upon. The next step, therefore, is an analysis of the tabulation by the Quality Control Section. A note is made of all items where a rejection, or

acceptance by waiver, has been made. This is done for all vendors. Each vendor's process or quality average is compared to the established AQL desired.

A check is made of the Vendor Trend Chart (Figure 9) to determine if quality has been improving or deteriorating; and special conditions such as sorting, lab rejections, or salvage work are also noted. This chart shows the percent defective, total samples inspected, and total defectives for a two-year period. Its purpose is to permit the calculation of quality limits and to invoke tightened or reduced sampling. It also affords an excellent medium for discussions with the Purchasing Department and the vendor.

Send report to vendors

The Vendor Quality Control Report (Figure 8) is prepared and sent to the Purchasing Department. These reports are prepared for all vendors who had shipments rejected in the past month and have exceeded their AQL.

Items accepted on waiver are given special attention with a description of the defect and reason for acceptance. Likewise, repaired items have a description of the salvage operation, reason for repair and, where possible, the cost of the repair. In all cases of special acceptance, the supplier is cautioned against recurrence of the defect.

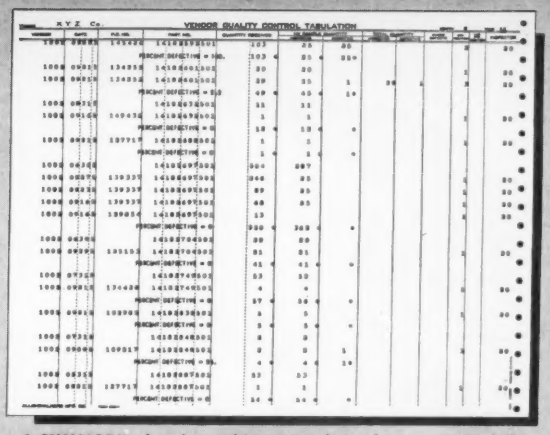
These reports are all forwarded to the Works Purchasing Agent for review and assignment to the purchasing agent dealing with the particular vendor. The purchasing agent forwards the vendor's copy with a letter requesting comments. The vendor, in turn, is obliged to reply, indicating his corrective action or when he will visit to discuss the problem. Copies of the vendors' replies to Purchasing are forwarded to the Statistical Quality Control Section and, where necessary, meetings are arranged for the vendor with Purchasing, Engineering and the Statistical Quality Control Staff to iron out the problems.

Vendors appreciate reports

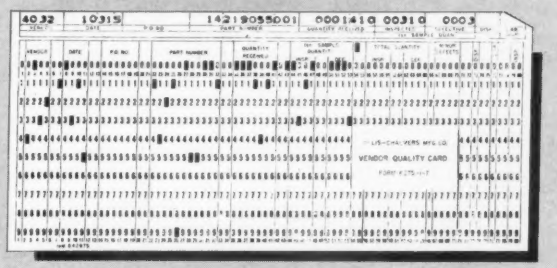
Meanwhile, the Engineering Department has been kept advised of troubles through copies of the reports and has had an opportunity to review designs on parts where trouble is frequent. They are also guided in future designs by knowing the history on troublesome parts and have the opportunity to prepare for discussions with the vendor on questions of design.

Vendors have been very enthusiastic towards this approach to controlling quality. They appreciate being advised of their troubles and quality standings. Many of them call regularly to discuss their quality standings, and they like the idea of being able to work out uniform inspection standards.

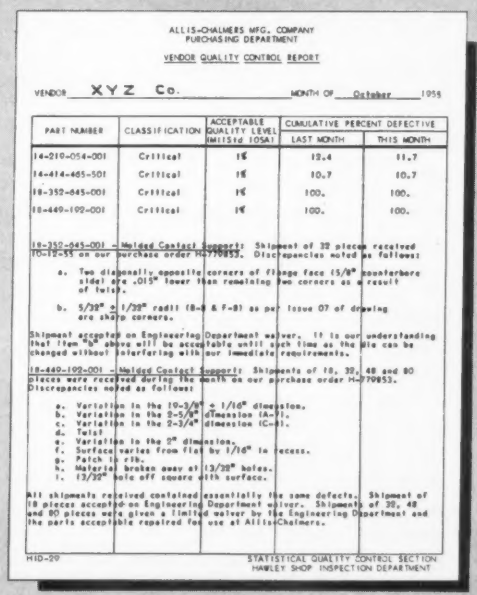
The benefits of Statistical Quality Control and tabulated reports have been threefold: uniformly high quality purchased materials get into production, thereby facilitating a high quality product and preventing shutdowns resulting from having to wait for defective material replacement; excellent relations between the Purchasing Department and the vendors have been established through closer personal contact with the vendors while helping them to solve their problems; and Receiving inspectors have been able to handle a better volume because of sampling techniques and improved quality of incoming materials.



A SUMMARY of each month's activity shows the quantity and the quality of all parts received from each vendor. **(FIGURE 6)**



PREVIOUS DATA are carried forward on monthly Summary Cards which are the basis of a continuous record for the year. **(FIG. 7)**



ALLIS-CHALMERS MFG. COMPANY
PURCHASING DEPARTMENT

VENDOR QUALITY CONTROL REPORT

VENDOR XYZ Co. MONTH OF October 1956

PART NUMBER	CLASSIFICATION	ACCEPTABLE QUALITY LEVEL (MIL STD 105A)	CUMULATIVE PERCENT DEFECTIVE	
			LAST MONTH	THIS MONTH
14-210-054-001	Critical	1%	12.4	11.7
14-414-465-501	Critical	1%	10.7	10.7
18-352-645-001	Critical	1%	100.	100.
18-449-192-001	Critical	1%	100.	100.

18-352-645-001 - Welded Contact Support: Shipment of 32 pieces received 10-19-56 on our purchase order H-779853. Discrepancies noted as follows:

a. Two diagonally opposite corners of flange face (5/8" counterbore side) are .015" lower than remaining two corners as a result of twist.

b. 5/32" ± 1/32" radii (B-6 & F-8) as per issue 07 of drawing are sharp corners.

Shipment accepted on Engineering Department waiver. It is our understanding that item "b" above will be acceptable until such time as the die can be changed without interfering with our immediate requirements.

18-449-192-001 - Welded Contact Support: Shipments of 10, 32, 48 and 80 pieces were received during the month on our purchase order H-779853. Discrepancies noted as follows:

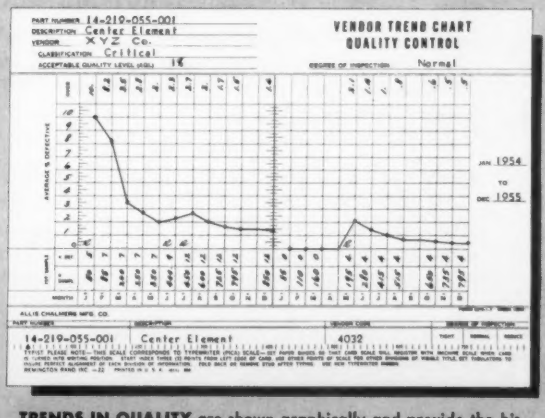
a. Variation in the 19-3/8" ± 1/16" dimension.
b. Variation in the 2-5/8" dimension (A-7).
c. Variation in the 2-3/4" dimension (C-8).
d. Twist.
e. Variation in the 2" dimension.
f. Surface varies from flat by 1/16" in recess.
g. Patch in rib.
h. Material broken away at 13/32" holes.
i. 13/32" hole off square with surface.

All shipments received contained essentially the same defects. Shipment of 8 pieces accepted on Engineering Department waiver. Shipments of 32, 48 and 80 pieces were given a limited waiver by the Engineering Department and the parts acceptable repaired for use at Allis-Chalmers.

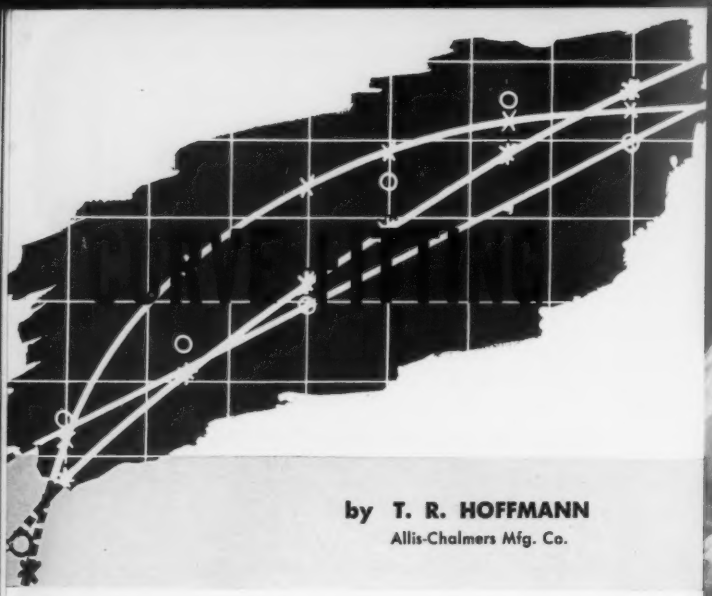
H10-29

STATISTICAL QUALITY CONTROL SECTION
HAWLEY SHOP INSPECTION DEPARTMENT

THE BASIS for Purchasing Department action is this report which indicates the quality maintained by each vendor. **(FIGURE 8)**



TRENDS IN QUALITY are shown graphically and provide the history of each vendor. Monthly summaries are entered. **(FIG. 9)**



by **T. R. HOFFMANN**
Allis-Chalmers Mfg. Co.

A SLIDE RULE, desk calculator, or straight-edge is all that's needed to determine the proper curve to represent empirical data.

Familiar equations and easy calculations enhance usefulness of empirical data and facilitate accurate graphic presentations.

ENGINEERS DEALING WITH NUMERICAL DATA gathered from tests, surveys, or observations commonly encounter the problem of fitting a curve to that data.

Raw data points seldom fall exactly on a familiar curve, but deviate to some extent. The object of curve fitting is to obtain a meaningful and useful representation by averaging out these variations. In doing so, engineers often resort to a complex freehand curve which passes through all of the raw data points or an equally arbitrary straight line fitted by eye. This results from the common belief that accurate, mathematical fitting of a curve is too complex and time consuming.

Fortunately, the relationships in many problems can be easily and accurately approximated by the familiar straight line, exponential, hyperbolic, parabolic, or logarithmic curves with great ease. These simple relationships should be looked at first. Other sets of data can be fitted well by geometric means. The following systematic approaches to arithmetic and geometric curve fittings make accurate curves easy to determine.

The straight line may fit best

Often data are best approximated by a straight line. But simply taking a straight-edge and trying to balance the points may result in a great deal of error. Fitting a straight line mathematically is much more accurate. The general formula for a straight line is:

$$Y = a + bX$$

where a and b are constants which specify a particular line (a is the Y intercept and b is the slope of the line). Since two constants must be determined, two equations are necessary. By means of calculus the following determining equations can be established so that the best fit is obtained:

$$Na + (\Sigma X)b = \Sigma Y \qquad (A)$$

$$(\Sigma X)a + (\Sigma X^2)b = \Sigma XY \qquad (B)$$

ΣX = the sum of all the independent variables.

ΣX^2 = the sum of all the squares of the independent variables.

ΣY = the sum of all the dependent variables.

ΣXY = the sum of the products of each independent variable and its corresponding dependent variable.

The best way to insure accuracy and speed in solving these equations is to set up a table of these factors. (See Table I.)

TABLE I

	X	Y	X^2	XY
Σ				

TABULATING the data simplifies calculations.

To solve these equations:

(1) Substitute the known factors into Eqs. (A) and (B).

(2) Multiply Eq. (A) by $\frac{(\Sigma X)}{N}$ to obtain another equation, (C).

(3) Subtract Eq. (C) from Eq. (B), eliminating the term containing a and leaving one equation, (D).

(4) Solve Eq. (D) for b.

(5) Substitute the value of b in Eq. (A) and solve a.

(6) Substitute a and b in the general equation.

Now to complete the procedure, determination of how well the curve approximates the data should be made.

Criterion of fit indicates accuracy

Although a common method of curve fitting is to draw a curve so that the sum of the differences between the data points and the corresponding points on the curve is a minimum, the most accurate representation of the data is a curve drawn so that the sum of the squares of the differences between the data points and the curve is a minimum. A measure of the "accuracy of fit" is the coefficient of correlation, R.

$$R = \sqrt{1 - \frac{\frac{\Sigma(Y - Y_c)^2}{N}}{\frac{(\Sigma Y^2)}{N} - \left(\frac{\Sigma Y}{N}\right)^2}}$$

Y = the data value of the dependent variable.

Y_c = the curve value of the dependent variable.

N = total number of data points used in constructing the curve.

ΣY = the sum of all the Y values.

ΣY^2 = the sum of the squares of each Y value.

$\Sigma(Y - Y_c)^2$ = the sum of the squares of the differences between Y and Y_c.

For convenience in computation, five more columns (Y^2, bX, Y_c, $Y - Y_c$, and $(Y - Y_c)^2$) can be added at the right of Table I.

R will always be less than $+1$. The closer R approaches 1.00, the better the curve represents the data. Correlation between 0.94 and 1.00 is normally considered satisfactory; correlations between 0.75 and 0.94 mean that another curve form or additional data points may be desirable. If R is computed to be the square root of a negative number, then a horizontal line through the middle of the data would have actually made a better representation than the curve that has been fitted!

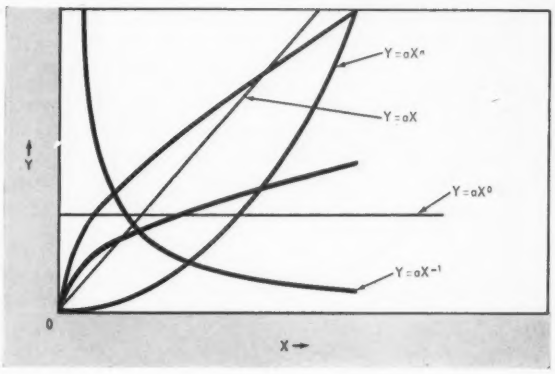
The exponential curve takes many forms

Many sets of data are better approximated by a curved line than a straight line. One of the most versatile curves of this class has the equation:

$$Y = aX^n$$

Depending upon the sign and magnitude of a and n, any of the curve forms in Figure 1 may be represented.

For example, if $n = 0$, then the curve is a horizontal straight line; if $n = 1$, then the curve is a straight line through the origin whose slope is a; if $n = -1$, then the equation represents a family of equilateral hyperbolas. As n takes on various values, a multitude of other curve forms will arise.



DATA of many types can be fit with the exponential curve. Calculations are easily done by means of a log-log slide rule. **(FIG. 1)**

It should be noted that this type of curve in most cases either passes through the origin or becomes infinite at the axis. These characteristics limit the use of the curve to data following a corresponding pattern.

The advantage of this versatile class of curves is that the best fitting curve form need not be known in advance when determining a and n; the calculations will automatically result in the proper a and n values for the best fitting curve of this type.

The equations to solve in obtaining a and n are:

$$\Sigma \log Y = n\Sigma \log X + N \log a \qquad (A)$$

$$\Sigma (\log Y \log X) = n\Sigma (\log X)^2 + (\log a) \Sigma \log X \qquad (B)$$

Set up a table as before with columns headed:

X, Y, $\log X$, $\log Y$, $(\log X)^2$, and $\log X \log Y$

(1) Substitute the values from the table into the Eqs. (A) and (B).

(2) Divide Eq. (A) by its coefficient of $\log a$, giving Eq. (A′). Divide Eq. (B) by its coefficient of $\log a$, giving Eq. (B′).

(3) Subtract Eq. (B′) from Eq. (A′) and solve for n.

(4) Substitute n into Eq. (A′) and solve for $\log a$.

(5) Find the antilog of $\log a$ and substitute a and n into the general equation.

(6) Compute the coefficient of correlation.

The hyperbola represents particular cases

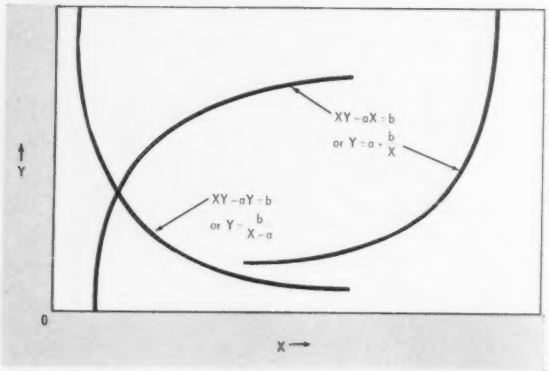
One special variation of the exponential equation which is quite useful and easily calculated is the equilateral hyperbola that can be moved about but not rotated. This curve overcomes some of the disadvantage of becoming infinite at the axis but still retains the property of approaching a limit. Two of the most useful forms of this curve are represented by:

$$XY - aY = b$$

and

$$XY - aX = b$$

This class of curves is shown graphically in Figure 2.



MANY PHYSICAL processes approach a limit and thus the hyperbola is a good curve to use in approximating the data. **(FIGURE 2)**

Again with two unknowns these curves require two equations to determine the constants. For $XY - aY = b$ use:

$$\Sigma XY - a\Sigma Y = Nb \qquad (A)$$

$$\Sigma X^2Y - a\Sigma XY = b\Sigma X \qquad (B)$$

For $Y = a + \frac{b}{X}$ use:

$$\Sigma Y = aN + b\Sigma\left(\frac{1}{X}\right) \qquad (A)$$

$$\Sigma\left(\frac{Y}{X}\right) = a\Sigma\left(\frac{1}{X}\right) + b\Sigma\left(\frac{1}{X}\right)^2 \qquad (B)$$

To solve either set of equations:

(1) Set up a table containing the factors called for in the equations.

(2) Substitute the values from the table into the equations.

(3) Divide each factor in Eq. (A) by the coefficient of b, thus getting Eq. (A′).

(4) Divide each factor in Eq. (B) by the coefficient of b, thus getting Eq. (B′).

(5) Subtract Eq. (B′) from Eq. (A′) and solve the resulting equation for a.

(6) Substitute this value of a into Eq. (A′) and solve for b.

(7) Substitute a and b into the general form.

Now compute the coefficient of correlation as before.

Geometric curve sketching is precise

Numerical data gathered from tests, surveys, or observations — or the processes themselves — may often indicate that a complex curve is the best representation or that the familiar curves do not fit as well as desired. In such instances a precise curve may be fit to the data by geometric means without calculations, particularly if the equation is not needed.

Usually when deciding whether a straight line, a hyperbola, or an exponential curve is best suited to a set of data, a picture of some curve is mentally "sketched." To assist in sketching a curve which itself is to be used in further study, some geometric techniques can be applied to achieve reproducibility and accuracy of fit.

(1) Plot the given data on graph paper.

(2) Label the points in order (*A*, *B*, *C*, *D*, etc.), starting at the left of the graph.

(3) Draw a straight line between every other point (*AC*, *CE*, *EG*, *BD*, *DF*, etc.) with a light pencil.

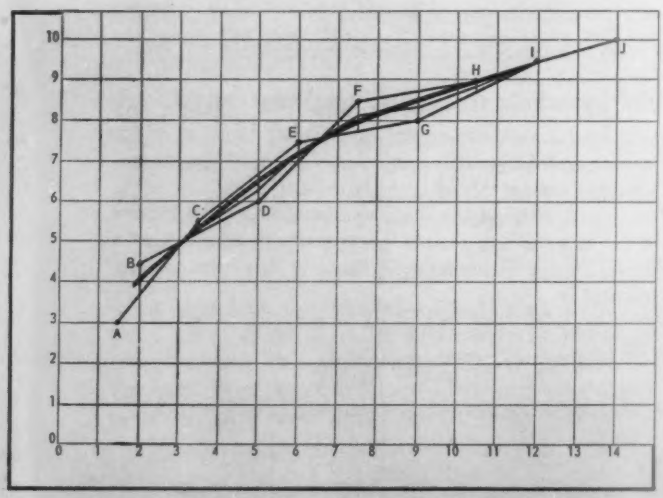
(4) At each of the given data points construct a short vertical line connecting both sets of straight lines.

(5) Indicate mid-points on these vertical lines.

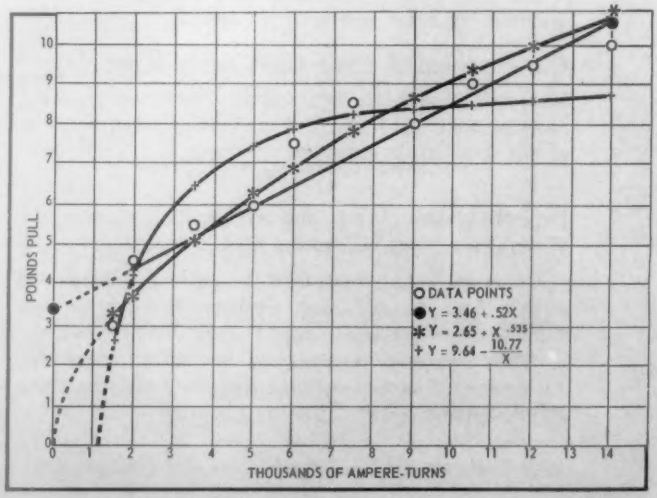
(6) Connect adjacent mid-points with straight lines.

(7) Using this new set of straight lines as a geometric guide, carefully sketch in a smooth curve. (See Figure 3 for example.)

When using this geometric technique, the origin of the data should be kept in mind and, generally, a smooth curve with few reversals of slope should be drawn. This procedure does not determine the curve outside of the second and second-last points because the data do not really tie



FREEHAND GEOMETRIC curve fitting is useful in representing data and insures duplicate fits by different analysts. **(FIGURE 3)**



SEVERAL CURVES can be drawn through a scattering of points. The inherent nature of the data determines which is best. **(FIG. 4)**

down the ends of the curve near the extreme points. If the coefficient of correlation for a geometric freehand curve is computed, it is usually extremely high.

The pull characteristics of an alternating-current magnet are an example of data which can be fit by either the straight line, exponential, or hyperbolic curves. Although all the curves might show good correlation, the known characteristics of the data should be considered and no points ignored. Figure 3 shows a freehand curve fit to the data in the tables below and Figure 4 shows the other curves fit to this set of data.

Application of these systematic techniques for finding the curve which best approximates empirical data will lead to more accurate curves and better utilization of data. The types of equations presented here are typical of others which can be used, such as parabolas and logarithmic curves.

$Y = a + bX$

	X	Y	X^2	XY	Y_c	Y^2	$Y - Y_c$	$(Y-Y_c)^2$
	1.50	3.00	2.25	4.50	4.24	9.00	−1.24	1.54
	2.00	4.50	4.00	9.00	4.50	20.25	.00	.00
	3.50	5.50	12.25	19.25	5.28	30.25	.22	.05
	5.00	6.00	25.00	30.00	6.06	36.00	− .06	.00
	6.00	7.50	36.00	45.00	6.58	56.25	.92	.85
	7.50	8.50	56.25	63.75	7.36	72.25	1.14	1.30
	9.00	8.00	81.00	72.00	8.14	64.00	− .14	.02
	10.50	9.00	110.25	94.50	8.92	81.00	.08	.01
	12.00	9.50	144.00	114.00	9.70	90.25	− .20	.04
	14.00	10.00	196.00	140.00	10.73	100.00	− .73	.53
Σ	71.00	71.50	667.00	592.00		559.25		4.34

$R = .953$

$Y = aX^n$

	X	Y	log X	log Y	$(\log X)^2$	log X log Y	Y^2	Y_c	$Y - Y_c$	$(Y - Y_c)^2$
	1.50	3.00	0 1761	0.4771	.031	.084	9.00	3.29	−.29	.084
	2.00	4.50	0.3010	0.6532	.091	.197	20.25	3.84	.66	.436
	3.50	5.50	0.5441	0.7404	.296	.403	30.25	5.18	.32	.102
	5.00	6.00	0.6990	0.7782	.489	.544	36.00	6.26	− .26	.068
	6.00	7.50	0.7782	0.8751	.606	.681	56.25	6.76	.74	.548
	7.50	8.50	0.8751	0.9294	.766	.813	72.25	7.80	−.60	.490
	9.00	8.00	0.9542	0.9031	.910	.862	64.00	8.60	−.33	.109
	10.50	9.00	1.0212	0.9542	1.042	.974	81.00	9.33	−.52	.270
	12.00	9.50	1.0792	0.9777	1.164	1.055	90.25	10.02	−.88	.775
	14.00	10.00	1.1461	1.0000	1.241	1.146	100.00	10.88	.70	.490
Σ	71.00	71.50	7.5742	8.2884	6.636	6.759	559.25			3.242

$R = .965$

$Y = a + \frac{b}{X}$

	X	Y	$\frac{1}{X}$	$\frac{Y}{X}$	$\left(\frac{1}{X}\right)^2$	Y^2	Y_c	$Y - Y_c$	$(Y - Y_c)^2$
	1.50	3.00	.667	2.000	.445	9.00	2.46	.54	.29
	2.00	4.50	.500	2.250	.250	20.25	4.26	.24	.06
	3.50	5.50	.285	1.571	.081	30.25	6.56	−1.06	1.12
	5.00	6.00	.200	1.200	.040	36.00	7.49	−1.49	2.22
	6.00	7.50	.167	1.250	.028	56.25	7.84	− .34	.12
	7.50	8.50	.133	1.133	.018	72.25	8.20	.30	.09
	9.00	8.00	.111	.889	.012	64.00	8.44	− .44	.19
	10.50	9.00	.095	.857	.009	81.00	8.62	.38	.14
	12.00	9.50	.083	.791	.007	90.25	8.74	.76	.58
	14.00	10.00	.071	.714	.005	100.00	8.87	1.13	1.28
Σ	71.00	71.50	2.312	12.655	.895	559.25			6.09

$R = .940$

SHINY BRASS TUBES — 3180 feet of them — produce no music in the motor stator but serve as an efficient heat exchanger. Rotor-mounted fans circulate outside air through the tubes. The stator is part of a vertical squirrel-cage motor rated 700 hp, 440 volts, 177 rpm. The machine will drive a circulating water pump in an East Coast power station.
Allis-Chalmers Staff Photo by Clarence Hansen

Periodic Circuit Breaker Tests

CUT MAINTENANCE COSTS

by E. R. PERRY
Southwest Region
Allis-Chalmers Mfg. Co.

Periodic circuit breaker maintenance can be replaced by simple tests.

THREE TESTS will indicate the condition of this 10,000-mva, 3-cycle, 1200-amp circuit breaker. It is not necessary to disassemble the breaker to determine its operating condition. **(FIG. 1)**

WHILE PERIODIC MAINTENANCE on large outdoor breakers has always been standard practice, actual testing is a more positive method of determining circuit breaker condition. Experience has shown that often more harm than good is done in breaker maintenance by partial disassembly. Failure to reconnect a blowout coil on an air-magnetic circuit breaker or failure to replace an interrupting device correctly on an oil circuit breaker can result in serious consequences. Less serious assembly mistakes during periodic maintenance work are much more frequent, and yet these, too, could be eliminated at a considerable saving in cost by performing simple tests on the circuit breaker.

Three functions are checked

There are three functions of a circuit breaker which must be checked:

1. Mechanical — timing, adjustment, and operating characteristics.
2. Current-Carrying Ability — contact resistance, shunt and bolted electrical connections.
3. Dielectric Strength — bushings and interrupting medium, i.e., oil.

Testing a circuit breaker's mechanical condition is relatively simple and can be done with accuracy. The test makes use of a direct-acting speedgraph taken from a recorder such as that shown in Figure 1. A direct-acting speedgraph is recommended rather than one with reducing heads, because it will provide more complete and accurate results when it is properly interpreted. A speedgraph not only indicates when mechanical difficulties are present, but also isolates the cause of the difficulties.

When a circuit breaker is first received from the factory, or when an older circuit breaker is being maintained, a thorough check for proper adjustment and a visual check for loose nuts or linkages are good practice. Immediately upon reassembly of the unit, a speedgraph should be taken for use as a master for future comparison. Where speedgraphs are available from the breaker manufacturer, they should be used as the masters. These masters should be filed and used for comparison of future speedgraphs on that particular circuit breaker.

Tripping and closing voltages should be checked before testing to make certain they agree with the master speedgraph record.

Speedgraph tests are taken on the phase or pole closest to the operating mechanism so that an accurate check on the operating mechanism itself is obtained. Speedgraphs taken on phases remote from the operating mechanism show certain inconsistencies due to linkage vibration and slack which make interpretation difficult. A slight change in characteristics foretells the possibility of more serious trouble in the making.

If a more thorough check is desired, speedgraphs should also be taken on poles remote from the operating mechanism. These additional speedgraphs will provide a check on the shock absorbers, overtravel stops, and adjustment of the other two phases. Speedgraphs taken on other than the phase closest to the operating mechanism cannot be interpreted as critically and should be compared only with master speedgraphs taken on the same pole.

Any deviation from the master, in subsequent speedgraph curves, shows some change in the mechanical operating characteristics of the circuit breaker. Proper interpretation of the curves indicates whether or not these changes are critical and what maintenance, if any, should be performed. The following methods of checking the mechanical condition of a circuit breaker hold true for air as well as oil breakers, and interpretation of speedgraph curves is accomplished by consideration of several zones, as shown in Figure 2.

Speedgraph interpreted by zones

Zone 1, concerning the trip mechanism, is the most critical of the zones. Any deviation in the test curve from the master speedgraph in this area should be investigated. Deviation between time zero and when the contacts first start to move will be caused by a change in trip voltage or sticking of the trip latch. Deviation during the rest of Zone 1 will be caused by the mechanical or pneumatic trip-free mechanism.

Zone 2 is a semi-critical zone. Arc interruption usually takes place in this area during the first four or five inches of travel after the contacts part on oil circuit breakers. Interrupting devices are designed for a specific contact part velocity. This velocity should not vary significantly from that measured at the time of breaker installation, and a change of more than plus or minus 10 percent should be investigated. Any slowing down of contact velocity within this zone can be caused by lack of lubrication causing binding in the operating mechanism, improper setting of the tail spring compression, a permanent set in the tail spring, or binding in the mechanical linkage. However, lack of lubrication or "gumming" of the operating mechanism is by far the most common cause. Extreme variations in temperature between the master and test speedgraphs will show a slight change in velocity. Factory speedgraphs are made at approximately 72 F.

Zone 3, shown in Figure 3, is the deceleration zone. This zone is not normally critical, but on large oil circuit breakers, 14.4 kv and above, the curve should be smooth and tapering, as shown in Figure 2. The shock absorber is contacted at the point where the curve begins to bend at the entrance to Zone 3. If the test curve falls below the master curve, there is probably insufficient oil in the shock absorber. If the test curve lies above the master curve, the shock absorber orifice may be clogged. On large oil circuit breakers, 69 kv and larger, this zone could be considered critical, as failure to decelerate properly could result in broken lift rods or crossarms.

Note reclosing operation changes

During a reclosing operation, any change in the curve during reversal of direction will indicate a change in the "b" switch setting or a change in the control-valve function when *Pneu-Draulic* or pneumatic operation is used. The point at which the "b" switch closes should be marked on the master speedgraph. This is done by placing a bell or light across the "b" switch and slowly lowering the breaker contacts until the switch closes. At this point the contacts should be held stationary and a line made on the speedgraph.

Zone 4 is the contact-make zone. Any sharp deviations from the master speedgraph indicate interference with the contacts. If this occurs, the circuit breaker should be opened and the contact alignment checked. Contact-make velocity should be measured in this zone as follows: Measure velocity between points one inch down from contact-make on the curve, and one cycle previous to this point on the curve. A decrease in contact-make velocity of plus or minus 10 percent is considered significant and should be investigated.

Zone 5 is controlled by the overtravel stop. Any increase in amplitude indicates a change in the overtravel stop adjustment. On most circuit breakers the overtravel stop is made easily accessible because it takes greater punishment than any other adjustment. A variation in amplitude of more than ¼ inch on a large circuit breaker should be checked and readjusted. A change in the damping of the bounce indicates a possible destruction of the resilient overtravel stop.

Zones 4 and 5 can also be checked by the use of a closing curve. Closing curve characteristics will not necessarily match up with the characteristics of a reclosing curve. Succeeding closing curves should match very closely, with no more than a plus or minus 10 percent variation.

Zone 6, the area covering the beginning of the breaker stroke on a single close operation, should also be considered.

Any deviation from the master curve will probably be in the slow direction. This indicates a sticking control valve, sticking solenoid or a high resistance in the control circuit. Contacts in the closing circuit can develop high resistance due to foreign matter or deposits built up by the arcing at the contacts.

TABLE I

MAXIMUM CONTACT RESISTANCE					
Air Magnetic Breakers			Oil Circuit Breakers		
Kv	Amperes	μ Ohms	Kv	Amperes	μ Ohms
5-15	600	100	7.2-15	600	300
	1200	50		1200	150
	2000	50		2000	75
			23-34	All	500
Note: Values vary with individual circuit breaker designs. Higher values measured on a particular design do not necessarily indicate an inability to properly conduct rated current.			46	All	700
			69	600	500
				1200	500
				2000	100
			115-230	All	1000

Current-carrying ability may change

The condition of the current-carrying components of a circuit breaker can be determined by the use of a low resistance ohmmeter reading in microhms. Limits for various ohmmeter readings on a wide variety of circuit breaker types have been published.[1] A rule of thumb schedule of maximum values is shown in Table I. If the contact resistance of a particular breaker measures slightly greater than the values shown, it does not necessarily mean trouble, for contact resistance varies with different manufacturers' designs and this must be taken into consideration. However, once a contact resistance test is made on a particular breaker, any large change in values over 150 percent during subsequent tests should be investigated.

In many ways a contact resistance check is similar to a power factor test of dielectrics. A sudden change in reading is often more indicative than the actual reading. Two meters are available for this test: the *Ductor* and the *Microhmer*. It is not recommended that these meters be used interchangeably, although either meter will give satisfactory results. At least 100 amperes should be used when making these tests.

The contact resistance check is made without dropping the tanks on an oil circuit breaker or without disassembly of an air magnetic circuit breaker. On an oil circuit breaker the meter probes are placed on the bushing studs with the circuit breaker contacts closed. The contact resistance is measured by a drop of potential method. Air circuit breaker contacts are measured in much the same way as the oil breaker contacts. The air circuit breaker is removed from its cubicle and the meter probes connected to the primary disconnects. Contact resistance measurements should be recorded on the speedgraph in order to keep records readily available. If high contact resistance is encountered, it is advisable to operate the breaker once or twice and then recheck the resistance reading before disassembling the breaker.

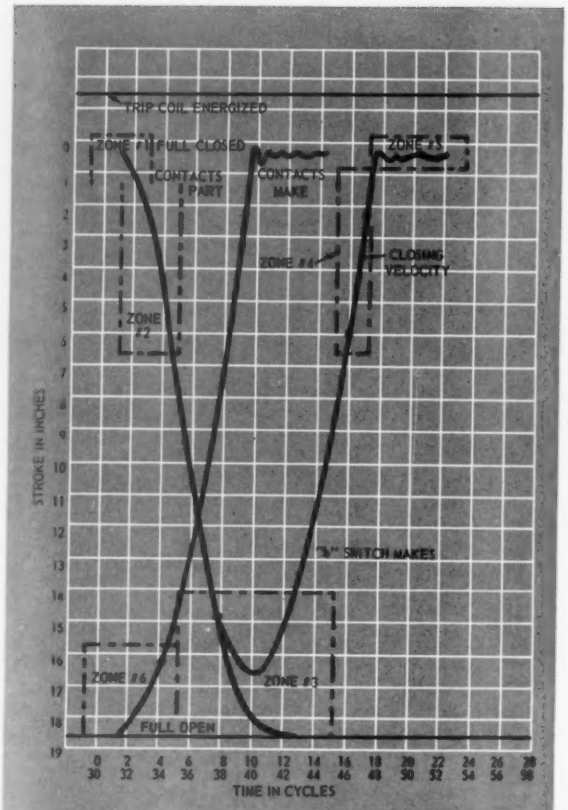
Megger tests show dielectric strength

The dielectric strength of a circuit breaker is checked by the conventional methods, such as power factor, oil dielectric breakdown, and Megger tests. These tests are covered in other articles and standards to the extent that it is unnecessary to elaborate here.

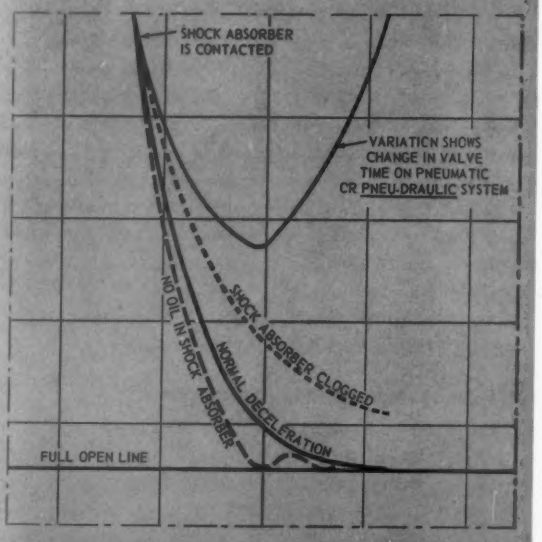
During testing, the control voltages and operating pressures in stored energy operators should be checked to insure that they are at the desired levels. An external visual check should be made for loose parts or signs of deterioration; bushings should be cleaned by wiping.

Periodic testing reduces maintenance cost and results in a more accurate record of the circuit breaker's condition. All of the tests outlined are used by a large number of utilities. A considerable amount of data and experience are available on each individual test method. By combining the tests as described here, a complete picture of the circuit breaker's condition is obtained, allowing a more intelligent scheduling of circuit breaker maintenance.

[1] *Electrical World*, May 17, 1954, p. 163.



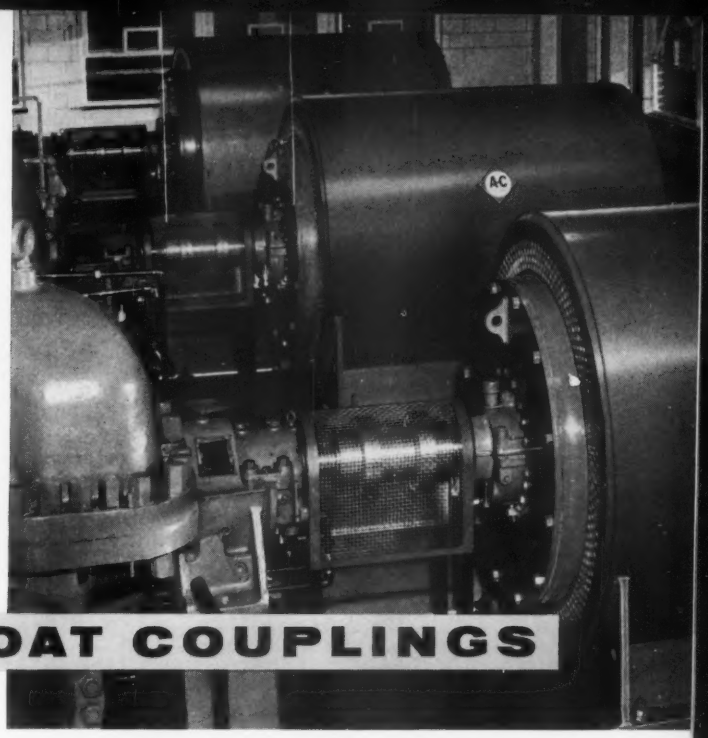
BREAKER OPERATION is divided into zones for interpretation of the speedgraph tests. Closing, opening and reclosing characteristics are shown for a 3500-mva oil circuit breaker. (FIG. 2)


SHOCK ABSORBER IS CONTACTED
VARIATION SHOWS CHANGE IN VALVE TIME ON PNEUMATIC OR PNEU-DRAULIC SYSTEM
NO OIL IN SHOCK ABSORBER
SHOCK ABSORBER CLOGGED
NORMAL DECELERATION
FULL OPEN LINE

CLOSE LOOK at Zone 3 shows variations that might result from improper operation of the shock absorbers during deceleration of large oil circuit breakers for which this check is important. (FIG. 3)

Solve Axial Thrust Problems with . . .

LIMITED END FLOAT COUPLINGS



MOTORS COUPLED TO PUMPS such as these explosion-proof pipeline machines are one of many applications where the limited end float feature is incorporated into flexible couplings. These tube-cooled, 1200-hp, 1780-rpm motors are installed in an oil pumping station.

by E. B. MILLS
Engineer-in-Charge
Induction Machines
and
J. E. PETERMANN
Motor & Generator Dept.
Allis-Chalmers Mfg. Co.

Good practice for most horizontal sleeve bearing motors requires flexible couplings with limited end float. Here's why.

AN IMPORTANT CONSIDERATION in the successful application of sleeve bearing electric motors is the selection of a flexible coupling to transmit torque from the drive motor shaft to the driven unit. Various types of couplings are available; however, certain precautions must be observed in applying some types to avoid bearing damage. In some instances, motor bearing damage may result from axial forces transmitted by the coupling back from the driven machine. A thrust bearing in the driven machine plus a limited end float coupling prevents this axial thrust from being transmitted to the drive motor shaft.

A limited end float coupling is defined as "a free-floating" type coupling in which the total relative axial movement of the hubs has been limited within the coupling itself to not more than one-half of the motor float. Although limited end float couplings are commonly considered new, they are, on the contrary, old and have been giving satisfactory service for over 25 years.

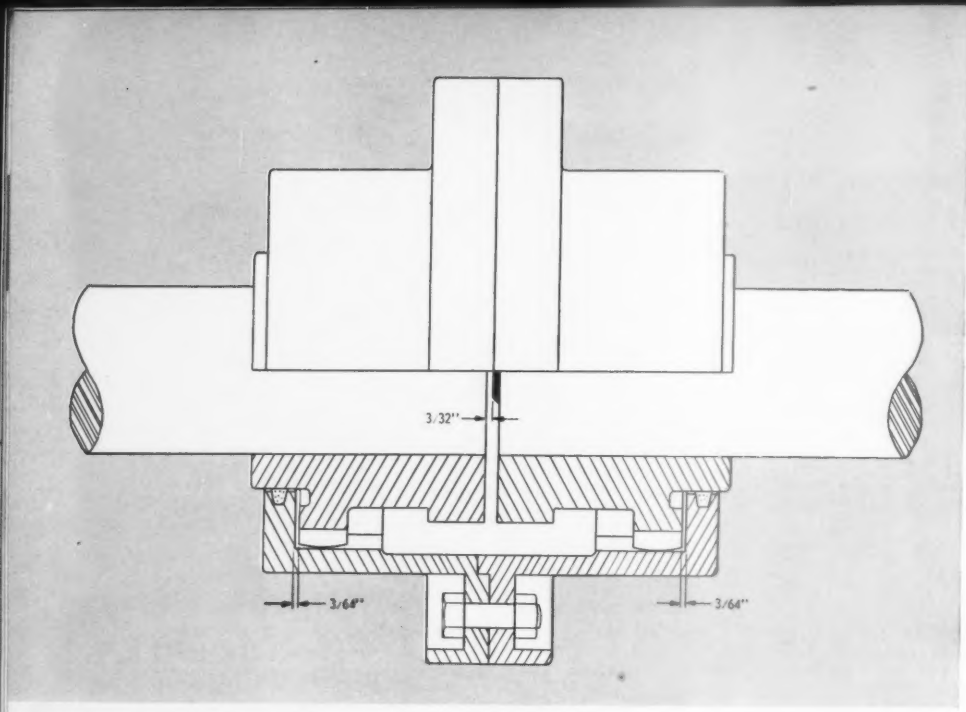
Unrestricted free-floating types of couplings, which include the pin and bushing type, the spring grid type, and the gear type, can present thrust problems. By adding a restraint to these couplings, they can be converted to the limited end float type, as shown in Figure 1. Self-positioning types of couplings are considered free from thrust problems and do not require mechanical stops. The laminated metal disc type coupling is a familiar example of the self-positioning type.

Thrust must be limited

In horizontal applications, such as hydraulic pumps, fans and compressors, driven machines as well as their drive motors have provision within their construction to position their own rotating element. A thrust bearing is normally used in driven equipment to restrain its thrust forces. End play of the driven machine is usually limited to a few thousandths of an inch, because of the close internal clearances that must be maintained.

Motor bearings, however, are designed to permit a relatively large rotor end play, or float, since the motor design does not impose restrictions requiring close axial clearances. One-half inch float is standard on larger machines. Furthermore, an electric motor develops a self-centering force which causes the rotor to run on magnetic center, and this force acts as a restoring force if the rotor is externally displaced from magnetic center. Of course, motors are assembled so the magnetic center is within the limits of float of the motor bearings, and the rotor of an uncoupled machine at rest may be anywhere within the allowable float limits.

Since the motor rotor is positioned or centered by magnetic forces during normal operation, there is no necessity for bearings designed to carry continuous thrust. There are several reasons, however, for providing some mechanical limitation on rotor float. First, it is necessary to prevent excessive axial travel of the rotor when the motor is



SMALL BUTTON on the end of one shaft serves to limit the float in one direction, while coupling separation is limited by lips on the coupling cover. Arrangement shown is for typical gear type coupling. **(FIG. 1)**

de-energized and coasting to rest. And second, depending on the initial position of the rotor relative to magnetic center, forces may exist during starting which will cause the rotor to "overshoot" the magnetic center.

Motor bearings have only limited thrust capacity

To limit rotor travel under either of the conditions, shaft shoulders are provided, and the end surfaces of bearing bushings are babbitted over the area with which the shoulders contact. Since it is essential that oil leakage from the bearing into the motor be minimized, the babbitted end surfaces are not provided with positive lubrication and cannot withstand continuous thrust load.

A typical standard motor bearing construction is shown in Figure 2. Nearly all of the oil discharged from the bearing is collected in the annular grooves near the ends of the bushing, and is drained back into the bearing housing through holes in the bottom of this annular groove. This prevents oil from being sprayed and atomized by the shaft shoulders and thus provides a very effective oil seal. The small amount of oil that escapes to the ends of the bushing wets the surface and provides sufficient lubrication for momentary thrust on start-up or for positioning the rotor while coasting.

The effectiveness of this bearing design to withstand any motor-imposed thrust forces is continually being demonstrated in applications where the motor is free of externally imposed thrust forces. Solid-coupled m-g sets, belted drive applications, and flexibly coupled drives with self-positioning type couplings are typical examples.

The concept that motor-developed thrusts must be carried externally because motor bearings are incapable of handling these thrusts is without basis.

Bearing damage can result from several causes

There are several possible ways that damaging external thrust may be imposed on motor bearings through unlimited end float couplings. One of the most common is through misalignment of the coupling. Misalignment causes the coupling hubs to pull together, or to separate, thus imposing thrust on both the motor and driven equipment bearings.

Another common cause of trouble is coupling locking. When the motor rotor is coasting to rest, it is free to float within the limits of bearing end play, since there is no torque on the coupling at that time. The rotor may stop with the shaft shoulder in contact with the bearing shoulder, and upon starting, the rotor will be held in position by friction resulting from torque at the coupling. This locking of the coupling is more effective at starting because of the increased starting current which increases the torque into the coupling. With worn or improperly lubricated couplings the locking tendency becomes greater. This condition can result in the rotor remaining out of its magnetic center. The magnetic forces tending to restore the motor rotor to its central position are small in comparison to the frictional resistance of the coupling to slipping axially. With the coupling locked, thrust conditions may be further aggravated due to thermal expansion of the shafts, especially if the thrust bearing of the driven machine is located at the outboard or end opposite the coupling end of the unit.

Thus the fundamental difficulty with unlimited end float couplings is that they permit conditions wherein two thrust bearings are loaded in opposition to one another. The magnitude of the thrust load on the motor bearings and the driven machine is equal to the force required to slip the coupling. The driven machine thrust bearing must then carry this coupling-imposed thrust plus its own thrust load.

With a limited end float coupling, the driven unit thrust bearing is subjected to no additional thrust unless the motor is being held off magnetic center. Even with the motor held off magnetic center the force is small — less than required to slip the couplings. Therefore, the driven unit thrust bearing is subject to less load with limited end float couplings than with unlimited end float couplings.

Thus it is to the advantage of the driven equipment as well as the motor to use a limited end float coupling.

The problems with free-floating couplings have been considered by a joint committee of the Hydraulic Institute and the National Electrical Manufacturers Association. Recommendations on the use of limited end float couplings were adopted and are now included in NEMA Standards. These recommendations are reproduced in Table I. Although specific reference is made to hydraulic pumps, the same principles are equally applicable on the other types of drives, including fans, centrifugal compressors, and so forth.

Variety of couplings serve same purpose

Limited end float models of the various types of free-floating couplings are available from several coupling manufacturers. The means of limiting the float depends on the type of coupling.

TABLE I
Taken from NEMA Standards MG1-6.11, Jan. 1957

Where motors are provided with sleeve bearings, the motor bearings and limited end float coupling should be applied as indicated.

Motor Horsepower	Synchronous Speed of Motor, Rpm	Minimum Motor Rotor End Float, In.	Maximum Coupling End Float*, In.
125 to 200, incl.	3600 and 3000	1/4	3/32
250 to 450, incl.	1800 and below	1/4	3/32
250 to 450, incl.	3600 and 3000	1/2	3/16
500 and higher	All speeds	1/2	3/16

* Couplings with elastic axial centering forces are usually satisfactory without these precautions.

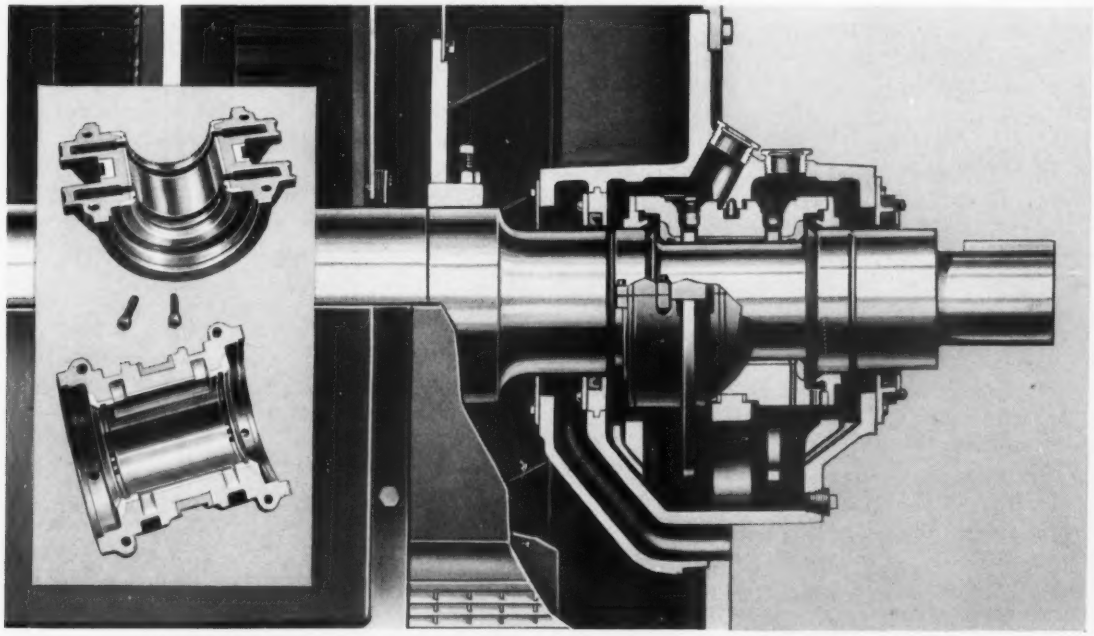
Pin and bushing type couplings may be limited through the use of two special pins located at diametrically opposite positions. A spacer washer is mounted on each of these two enlarged head pins.

The end float of spring grid-type couplings can be limited with spacer plates or buttons located between shaft ends in conjunction with half oval soft steel or copper inserts or "rung-spacers" placed in the loops of the springs. These rung-spacers are located symmetrically to maintain balance.

Gear-type couplings may be limited through the use of spacer plates or buttons, as shown in Figure 1. Hollow spacer-type couplings require plates at each end of the spacer. Thrust tending to bring the coupling halves together is restrained by the buttons. Thrust tending to separate the two halves of the coupling is restrained by lips located at the ends of the coupling cover.

Although the above methods are preferred for limitation of end float in free-floating types of couplings, spacer plates or buttons may be omitted at the user's discretion. The end float of free-floating type couplings can then be limited by overpressing one or both coupling hubs to locate them farther back on the shaft, thus allowing the shaft ends to protrude slightly through the coupling hubs. With this arrangement care must be exercised to get the hubs back in the same location should they be temporarily removed for maintenance or other reasons.

This latter means of limiting coupling end float is one which is generally readily adaptable on existing installations on which it is desired to incorporate the limited end float feature. No new or additional parts are required, since it can be accomplished simply by overpressing the



THRUST FACES on the shaft at each end of the journal serve in conjunction with the babbitted ends of the bearing to limit motor float but are not intended to withstand a continuous axial thrust load. **(FIG. 2)**

coupling hub slightly and repositioning the motor slightly toward the driven machine.

Standard alignment methods are used

The alignment of a motor when using a limited end float coupling is simple and straightforward. It requires no more time, effort, or degree of accuracy than is needed to properly align machines using nonlimited end float couplings. Figure 3 in conjunction with Table II shows a method of making proper setting of the motor in relation to the driven shaft. While the schematic arrangement is shown with the gear-type coupling, the arrangement also applies to pin and bushing and spring grid-type couplings. The coupling is shown in the closed position. Normal coupling operation may be fully closed, fully open or at some intermediate position.

While the dimensions in Table II are for nominal values of motor end play, motor end play has some tolerance and may vary slightly from the nominal value. An instruction plate on the motor gives data on the actual end play when a limited end float coupling is required. Any variation of the actual end play from nominal should be divided equally between dimensions *A* and *B*. When aligning machines having self-positioning type couplings, the motor must be located relative to the driven unit so that the motor shaft is in the center of its end float. Referring to Figure 3, *B* will equal *C*.

TABLE II
COUPLING AND BEARING SETTINGS
(Dimensions in Inches)

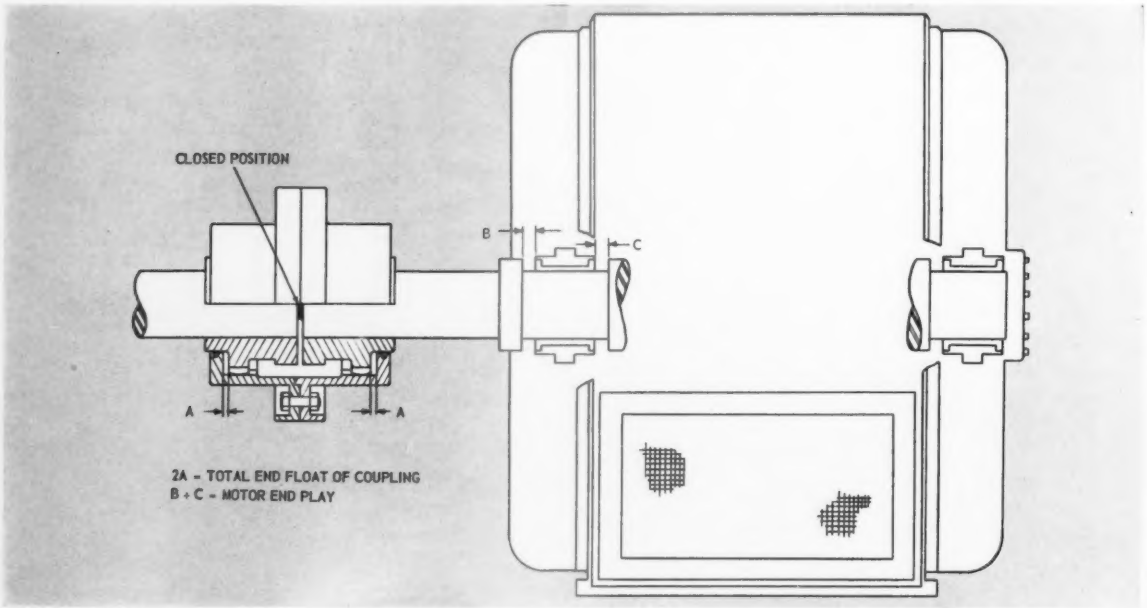
Nominal Motor End Play	Limited Coupling End Float	A	B	C
1/2	3/16	3/32	11/32	5/32
1/4	3/32	3/64	11/64	5/64
		With motor half coupling located midway of total coupling end float, instead of closed coupling, make B = C.		

After positioning the motor to obtain the proper axial setting, an accurate shaft alignment must then be established.[1] Alignment should be made so that the motor shaft and driven unit shaft are in line at normal operating temperatures. Compensation must be made for any temperature differential that exists between the units. To assure that the desired alignment has been achieved, a final "hot" alignment check is made immediately after a shutdown from a prolonged run under normal operating conditions.

Limited end float couplings are a must for economy and good design

It has been pointed out that a motor, as an independent uncoupled machine, does not require a thrust bearing. The expense of providing a motor thrust bearing, which would be added to the motor cost, is an additional consideration. Since motor thrust bearings must be lubricated, they complicate the problem of keeping oil out of the motor itself. In addition, providing two thrust bearings in series, one on the driven unit and one on the motor, is generally considered to be poor mechanical design practice.

[1] "Align Shafts, Not Couplings," W. F. King and J. E. Petermann, Allis-Chalmers *Electrical Review*, 2nd Quarter, 1951.



SHAFT ALIGNMENT of motors with limited end float couplings requires the same care as with machines without this feature. Table II shows this correct relationship of motor bearing and coupling clearances for correct axial positioning. **(FIGURE 3)**

Three-Phase Power Transformers Gain Popularity

by E. G. ASHBAUGH
Pittsburgh Works
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Today three-phase power transformers are selected almost exclusively because they reduce substation erection, operation, and expansion cost.

PRESENT TRENDS indicate a growing use of three-phase power transformers because of savings in cost and space. The cost of a single three-phase unit is about 95 percent of that of three single-phase units and 72 percent of four single-phase units. Other advantages include lower foundation costs and, in many cases, simpler station layouts.

The recent bond offerings by utility companies show that high interest rates are making it more important than ever that equipment be purchased for maximum economy. Since utilities have had to expand their generating capacity anticipating future growth, there may be less capital available for purchasing the new equipment necessary for expanded facilities.

Twenty-five years ago the majority of power transformers were single phase. Loss of a single-phase unit at best meant a loss of 42 percent of connected load as compared to the complete loss of load fed by a three-phase bank.

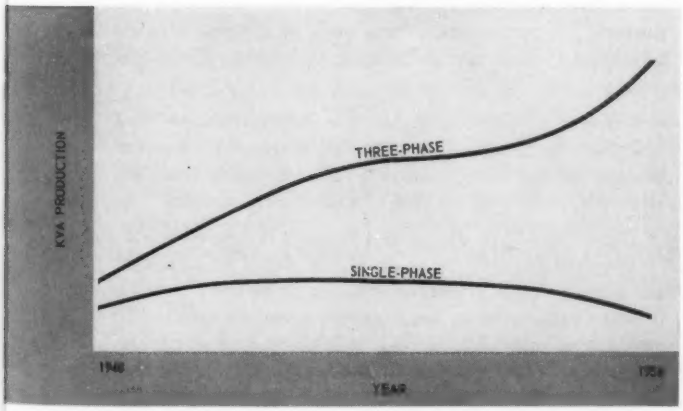
The usual practice was to have a single-phase unit as a spare. Many users also had power transformers equipped with wheels so the spare unit could be quickly installed when failure occurred. The more intelligent use and better quality of insulating materials have made the number of power transformer failures negligible. If failure should occur, the interconnections of power systems and networks take over to insure uninterrupted service. Utilities are contributing much to the trend toward three-phase transformers as well as making a more efficient and economical use of their power equipment. The three-phase unit does the job well and can be fitted into the space occupied by the single-phase bank.

The operating costs of three-phase and single-phase power transformer installations are, for all practical purposes, the same for lightly loaded systems, with core losses being relatively constant. Savings of from 5 to 30 percent in annual operating costs are realized when three-phase power transformers are used in fully loaded systems, because there is less copper in them and copper losses increase with the load.

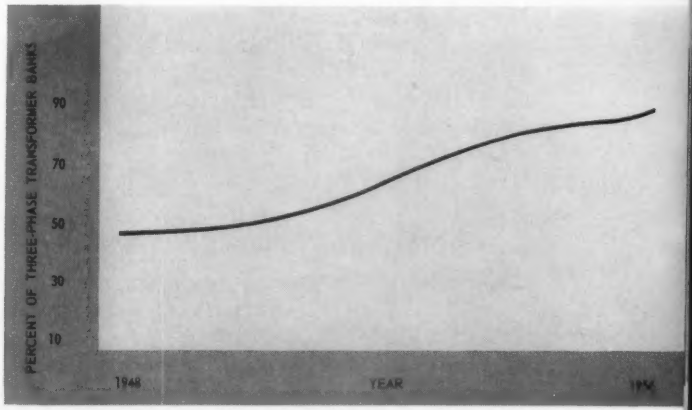
Since a three-phase power transformer is larger and heavier than a single-phase transformer of equal capacity, transporting and erecting a three-phase unit is apt to involve additional problems of blocking, clearance limitations, and weight restrictions.

The cost of erecting a new substation using three-phase transformers rather than single-phase units is less, primarily because there are fewer units to be installed. In many instances when there is sufficient demand for increased power it is desirable to have the three-phase unit available.

All signs point to continual population growth with accompanying industrial expansion. As urban and industrial expansion continues and land for system expansion becomes less available, the trend toward three-phase transformers will continue. Figure 1 shows the increase in three-phase capacity and the decrease in single-phase capacity, while Figure 2 combines the curves in Figure 1 to show the overall three-phase increase.



THREE-PHASE TRANSFORMERS are showing an ever increasing popularity over single-phase units. Smaller installations will become more necessary as our population continues to grow. **(FIGURE 1)**



THE INCREASING GROWTH OF THREE-PHASE capacity indicates the effect of more three-phase installations in recent years. This trend should continue as utilities keep expanding. **(FIGURE 2)**

Engineers Discuss...

DOLLAR DYNAMICS

INSTRUCTOR EXPLAINS the break-even chart, one of the many useful tools presented the engineers.

by **STEPHEN M. HILL**
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Young engineers' management potential is bolstered through classroom conferences and the review of current publications.

COMPANIES DEALING WITH TECHNICAL PROBLEMS arising from highly engineered products find young engineers are potential managers. The very fact that they have been graduated from an accredited engineering school indicates that engineers have above-average mental capacity and possess analytical tools useful to anyone in a managerial position.

However, the engineer's greatest strength — reducing problems to mathematical and scientific terms — frequently proves the greatest stumbling block to his career in management. Unfortunately, most managerial problems concerning dollar dynamics cannot be reduced to such precise terms.

Since the problems cannot be made entirely objective, a subjective approach to the problems of economics and business must be added to the engineer's objective thinking.

While seemingly rather fundamental, this proper perspective of the business world may take a long time to acquire through experience; to shorten the length of time needed to acquire this viewpoint, an economics and business training course is offered as part of the graduate training program for young engineers.

Present additional tools to engineers

The course is designed to give the engineer, in ten 4-hour sessions, tools which he can use whether in design engineering, sales engineering, or management. Some tools are rather subjective (how to obtain more information from business publications), other tools (what to look for on a departmental profit and loss statement) are more akin to the familiar tools of engineering.

As might be surmised, the tools actually provide the section heading around which the course is designed. At the same time, the "broad" approach is developed through the general teaching philosophy employed in the course. The conference method, led by a qualified instructor, allows each man to voice his opinions and to think freely.

Showing the young engineer how this firm actively fits into the general economic picture is the foremost purpose of the course. This dynamic view of economics as a living part of the progressive business world brings the entire subject to life.

The course jumps right into a look at the American economy of today. This is done by tracing the strides that the economy has made since its last major setback in the thirties. The text material for a study of this sort is based largely on current magazines, such as *Business Week* and *Fortune*.

Standard economic terms, such as "utility creation" and "diminishing returns," are discussed to give the students background for outside reading. The emphasis, however, is on the analysis of the American economy of today.

The standard first course in economics is covered in two or three weeks, with special emphasis placed on areas that are likely to cause confusion later (such as the difference between production in the economic sense, the creation of anything of value; and production in the engineering sense, manufacturing). Only enough is said to awaken further interest in areas which are covered in other parts of the course.

After the fundamentals of economics are covered, the course goes on into more detailed study of other fields of business and economics. Among these are accounting, finance, marketing, business law, and government and business.

Discuss accounting and budgeting

In each subject area, the material is geared as closely as possible to the use that the trainee is likely to make of it. As none of them is likely to ever work as an accountant, the emphasis in discussing accounting is from the user's side. The students study the company's own accounting forms and pay close attention to the details of a departmental profit and loss statement and a sales office expense report. Knowledge of the importance of the various parts of these reports will help the young engineer long before he is a department or sales office manager, because the better he understands expenses the better he can control them.

Budgeting, which is the planning of tomorrow's profit and loss statement today, is covered right along with historical accounting; thus, accounting is considered to be a living management tool as well as a record of what has happened in the past.

In looking at company-wide records in addition to those for an individual department, the emphasis is again on the company's own statements. These are studied largely as they appear in the annual and quarterly reports issued by the company. Similar statements of other companies in the same industries are also studied.

At this point in the course, the transition from accounting to finance is readily made. Study of the long-term liability and capital accounts of the company almost inevitably leads directly into a discussion of what large companies do to get the money with which they operate.

Finance is covered both from the standpoint of the man who must raise the funds and the man who must employ them in his activities. Engineers show keen interest in the several four-hour sessions spent discussing financial transactions, corporate ownership, and the workings of the stock market. It is at this time that the *Wall Street Journal* and other sources of financial information are studied thoroughly for the financial information they contain, and for the thorough coverage they give to all phases of business.

Appraise personal finance plans

Also included in the financial section is a discussion of personal investments. While recommending no specific type of investment, the course instructors are careful to point out the advantages and disadvantages of all types of investments in a man's program at various points of his financial development. An appraisal of the investment side of life insurance is included, along with the place of stocks, bonds, real estate and personal property in an individual's holdings.

The study of marketing is centered around case histories gathered by the class. For his project each member familiarizes himself with the marketing methods used in connection with a specific company product. He studies the complete scope of the market for the product he is assigned, plus each of the ways in which that market is reached. The marketing problems and the ways in which they are solved give a complete course in industrial marketing through the description of fifteen or twenty case histories.

Two important fields are brought to the student's attention in the discussion of business law. The first centers around the various legal positions (such as acting as an agent for the company) in which the trainee may some day find himself. The second covers some of the patent situations which the engineer-manager is likely to encounter.

Study government and business

The main purposes of the legal part of the course are to help the young engineer avoid putting himself, and the company, into an embarrassing legal situation and to help him recognize when he should seek legal help.

A thorough discussion of government and business is included in the course because of the importance of the federal government as a customer, competitor, arbiter, taxing authority, and source of information in the business world. This section is designed to enable the young engineer to cope with the problems which arise because of the present size of government operations. The emphasis is entirely nonpolitical, and the stress is laid on the practical aspects of dealing with government.

Having the young engineer see how his firm fits into the business community may pay immediate dividends to the organization; however, broadening the engineer's viewpoint to include subjective analyses usually involves a longer period before reaping benefits.

Probably none of the engineers trained in this course will assume management positions for at least five or ten years, but the foundations of management thinking and dollar dynamics have been laid. This understanding of the business community of our nation is important to the development of not only future managers, but also future design and sales engineers.

MAGAZINES, NEWSPAPERS and other current literature form the basis for discussion of the present trends in American economy.

Variable-Speed Drives Using A-C Equipment

by **HARLAN S. NEUVILLE**
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Wound-rotor motors used as frequency converters have definite advantages in certain variable-speed drive applications. Here is basic application theory.

THE ADVENT OF AUTOMATION plus the need for high-speed drives to test aircraft components has resulted in an increasing emphasis on the use of ac equipment for variable-speed applications. Induction frequency converter drives are finding acceptance for these special applications.

Two advantages of using alternating-current equipment for variable-speed applications instead of the more common variable-voltage drives are:

1. Most industrial installations have a ready supply of three-phase alternating current.

2. Dc variable-voltage equipment is limited to lower voltages and speeds because of commutation problems.

The most obvious method of reducing speed of a cage motor would be to reduce the frequency applied to its armature. The lower the frequency, the slower is the three-phase rotating field on the motor armature and, hence, the slower the rotor speed. If, however, lower frequencies are applied with the terminal voltage remaining constant, excessive current will flow and there is the possibility that the thermal capability of the motor might be exceeded.

Reducing the voltage applied to the armature of a squirrel-cage motor might be another method of reducing speed. For instance, if 90 percent of rated voltage were to be applied, the motor could produce only 81 percent of its rated torque. This would result in a droop in the speed-torque curve and the rotor would readjust at a different speed to balance the load torque against the electromagnetic torque developed by the motor. The voltage reduction method is limited to very small speed ranges because it reduces the torque capability of the squirrel-cage motor.

If, however, the voltage and the frequency applied to the armature of the cage motor were lowered in the same quantities (constant volts per cycle), the characteristic of the cage motor would remain essentially the same. This generalization holds only when the stator and rotor impedances are not major current-determining factors in a motor and is valid only when the load is the main consideration in determining current. As shown in Figure 1, the characteristics of a cage motor would remain essentially the same while constant volts per cycle are applied. By lowering the torque characteristics of the machine, the motor will assume a new speed at which the capability of the motor matches the load.

Constant volts per cycle generator needed

One arrangement used to produce constant volts per cycle variable frequency makes use of the wound-rotor induction motor as a generator.

The drive arrangement for producing variable frequency from the rings of a wound-rotor induction motor is shown in Figure 2. Driving the induction converter is a squirrel-cage induction motor in conjunction with an eddy-current clutch and brake. Basically, the wound-rotor motor acts as a frequency converter.

If the rotor of the wound-rotor machine is braked to speeds less than the synchronous speed of three-phase rotating field on the converter armature, a range of frequencies from 0 to 60 cycles appears across the rotor rings. The 60-cycle frequency would occur when the rotor was at a standstill. This condition is shown in Figure *A*.

If the rotor of the induction frequency converter is driven in the opposite direction from its three-phase rotating field, frequencies higher than 60 cycles are produced. When the rotor is driven in the direction shown in Figure *3B* at synchronous speed, frequencies of 120 cycles are generated.

In applying this line-up of equipment for variable-speed applications, the relationship between power out of the rings, power into the converter across the air gap, and power into or out of the converter shaft must be known. An understanding of what occurs in the driven converter

can be obtained from equivalent circuit parameters when assuming that the losses can be ignored. There are three general types of loads driven by induction motors:

1. A variable-speed load in which the torque remains constant. (Constant torque or machine load.)

2. A variable-speed load in which the horsepower remains constant. (Constant horsepower load.)

3. A variable-speed load in which the horsepower is variable. In this case the characteristics of a fan whose horsepower varies with cube of the speed will be reviewed. (Fan or centrifugal pump type load.)

After the type of load is established, the ratings of the converter and its supporting equipment can be readily determined. Figure 4 illustrates the conventional per phase equivalent circuit used for induction machines. In this circuit the load is represented as a resistance between the rings of the converter.

The per phase current which flows in the secondary of this circuit is given by the formula

$$I_2 = \frac{sE_2}{R_2 + jsX_2} \qquad (1)$$

where s represents the percent slip of the rotor. It is important to emphasize that the frequency which exists in the rotor circuit of any induction machine is equal to the percent slip times the frequency applied to the armature of that machine. Since most machines are applied to 60-cycle systems, the frequency will be the slip times 60. If a cage motor were connected between the rings of a wound-rotor motor, the cage motor would be driven by the frequencies induced in the rotor of the wound-rotor machine.

The speed of the cage motor would therefore be directly proportional to the frequencies induced in the secondary of a converter. Hence, the load applied to the ultimate cage motor varies as the cube of the speed, or in other words the load varies as the slip of the converter rotor cubed. The induced voltage of the converter rotor in Eq. (1) is also a function of the slip. Thus the converter rotor is inherently a constant volts per cycle generator, since both ring voltage and ring frequency are a function of the converter rotor slip.

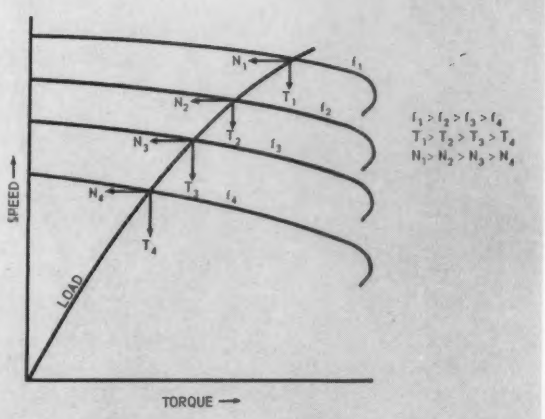
Equation (1) can be rearranged as:

$$I_2 = \frac{E_2}{R_2/s + jX_2} \qquad (2)$$

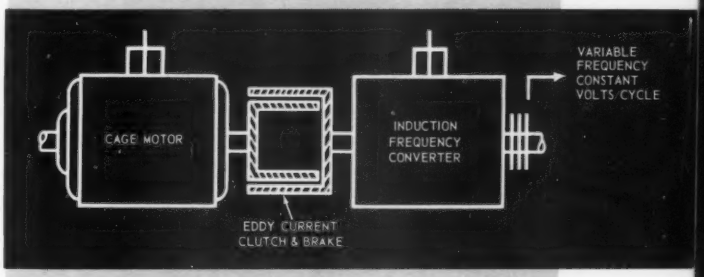
From theory the quantity R_2 over s is recognized as the total apparent resistance which appears in the rotor of the converter. This resistance includes the real resistance of the rotor itself and a hypothetical resistance representing the load placed across the converter rings. Therefore the real power into the rotor of the frequency converter is the function of the current squared and the total resistance of the converter rotor circuit.

$$\text{Power}_{in} = \frac{I_2^2 R_2}{s} \qquad (3)$$

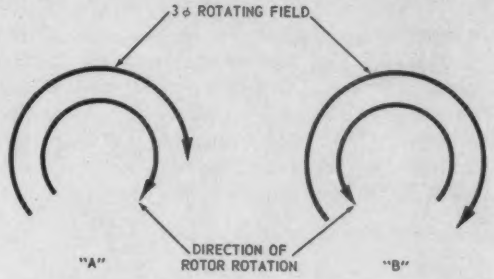
Since the hypothetical resistance representing load is so much greater than the real resistance of the converter



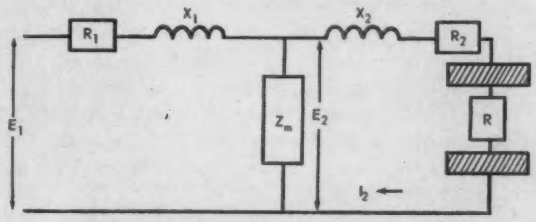
CONSTANT VOLTS PER CYCLE voltage and frequency changes produce a consistent set of cage motor speed-torque curves. **(FIG. 1)**



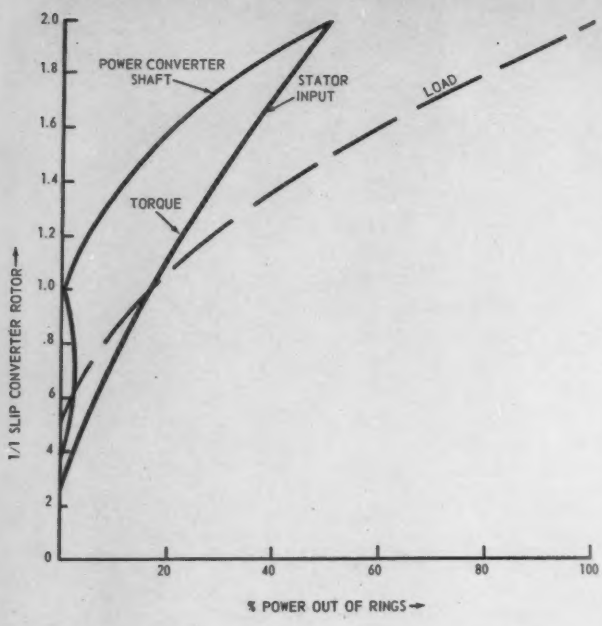
INDUCTION FREQUENCY CONVERTER rotor speed is controlled through a cage motor driven eddy-current clutch and brake. **(FIG. 2)**



SPEED AND DIRECTION of the converter rotor determine the frequency and voltage of the output from the rotor rings. **(FIG. 3)**



EQUIVALENT CIRCUIT of induction machine determines the power flow. *R* represents load resistance between rotor slip rings. **(FIG. 4)**



CONVERTER CHARACTERISTICS for a fan load determine physical size of drive. Power into converter shaft is less at reduced speeds. **(FIG. 5)**

rotor, we can consider the power loss in the converter rotor as made up entirely of the rotor current squared times the hypothetical resistance representing load. This power loss in the converter rotor circuit can be expressed by the following equation:*

$$P_{rings} = I_2^2 R_2 \qquad (4)$$

The power at the shaft in terms of Eqs. 3 and 4 is the difference between the power into the rotor and that which is lost between the rings. This is expressed as

$$P_{shaft} = \frac{I_2^2 R_2}{s} - I_2^2 R_2 = I_2^2 R_2 \left(\frac{1}{s} - 1\right) \qquad (5)$$

Two relationships necessary for applying our converter to various types of loads can now be developed. The first relationship is expressed in Eq. (6) which states that the power of the shaft is equal to the power at the rings times 1 minus s over s. The second relationship is that the power into the stator, ignoring losses, is equal to the power which must appear at the rings divided by the slip.

$$\text{Power shaft} = \text{power rings} \times \left(\frac{1-s}{s}\right) \qquad (6)$$

$$\text{Power stator} = \text{power rings} \times \frac{1}{s} \qquad (7)$$

With these relationships, we can derive the equations relating to power flow in an induction frequency converter for the three types of loads.

The first type of load is one in which the power varies as the cube of the speed such as with a fan or centrifugal pump load. Since power varies as the speed cubed, it also varies as the slip of the converter cubed. Thus, in Eq. (7) the power of the rings is replaced by a constant times the slip cubed, as shown in Eq. (8).

$$\text{Power stator} = ks^3 \times \frac{1}{s} = ks^2 \qquad (8)$$

* Equations relate motor parameters assuming no losses, and as such are not valid for design purposes.

TABLE I

Slip Data for Figure 5

s	s^2	s^3	$1 - s$	$s^2(1 - s)$
0	0	0	1.0	0
.2	.04	.008	.8	.032
.4	.16	.064	.6	.096
.6	.36	.216	.4	.144
.8	.64	.512	.2	.128
1.0	1.0	1.0	0	0
1.2	1.44	1.728	— .2	— .288
1.4	1.96	2.74	— .4	— .785
1.6	2.56	4.09	— .6	—1.536
1.8	3.24	5.84	— .8	—2.59
2.0	4.0	8.0	—1.0	—4.00

In terms of ring power

Power stator $= s^2/8$

Power rings $= s^3/8$

Power shaft $= s^2(1 - s)/8$

Torque shaft $= s^2/8$

Also, if we were to replace the power of the rings in Eq. (6) with a constant times s cubed, the power for the shaft of the converter would vary as the slip squared times the quantity 1 minus the slip.

$$\text{Power shaft} = ks^3 \times \left(\frac{1-s}{s}\right) = ks^2(1-s) \qquad (9)$$

To obtain the torque to the shaft of the converter, the power of the shaft is divided by the quantity 1 minus s. This relation is expressed in Eq. (10):

$$\text{Torque converter shaft} = ks^2 \qquad (10)$$

Four fundamental equations provide the relationship of power flows in a converter when a fan-type load is applied to the converter rings through the load drive motor. Ignoring losses for fan load, these equations are:

Power rings $= ks^3$

Power into stator $= ks^2$

Power shaft $= ks^2(1 - s)$

Torque shaft $= ks^2$

A clear picture can be obtained from a graph of these power flows in terms of the per unit ring power.

A converter frequency range of approximately 120 cycles to 0 cycles was chosen for illustration purposes. The same general theory applies for either a smaller or larger frequency range. Assuming that the fan load is 100 percent at the 120-cycle point, or in terms of slip it is 100 percent at a slip of 2, the power output from the rings can then be shown graphically as an ordinary cubic function. Figure 5.

Since the original power is 1 and the original slip cubed is 8, the power of the rings is plotted as a function of the slip cubed divided by 8.

Percent power rings $= ks^3$

1 — represents initial condition

2 — represents second condition

$$\frac{P_{r1}}{s_1^3} = \frac{P_{r2}}{s_2^3}$$

$$P_{r2} = \frac{s_2^3}{s_1^3} P_{r1} = \frac{s_2^3}{8} \times 1 = \frac{s_2^3}{8}$$

Power into converter plotted

Since the initial power out of the rings is s cubed over 8, the power into the stator of the converter will be s cubed over 8 divided by s or s squared over 8.

Power stator $= ks^2$

$$\frac{P_{s1}}{s_1^2} = \frac{P_{s2}}{s_2^2}$$

$$P_{s2} = \frac{s_2^2}{s_1^2} \quad P_{s1} = \frac{s_2^2}{s_1^2} \quad \frac{P_{r1}}{2}$$

$$P_{s2} = \frac{s_2^2}{4} \times \frac{1}{2} = \frac{s_2^2}{8}$$

The power into the shaft is plotted in terms of per unit ring power also. This derivation is shown below.

Power shaft $= s^2(1-s)$

$$\text{Power shaft}_1 = P_{rings1}\left(\frac{1-s_1}{s_1}\right) = 1\left(\frac{1-2}{2}\right) = -\frac{1}{2}$$

$$\text{Power shaft}_2 = \frac{s_2^2(1-s_2)}{4(1-2)} \times \left(-\frac{1}{2}\right)$$

$$\text{Power shaft}_2 = \frac{s_2^2(1-s_2)}{8}$$

The chart for various values as plotted in Figure 5 is shown in Table I.

The power flow to and from the converter shaft is motoring in nature above 60 cycles and braking in nature below. Thus, the converter prime mover in Figure 2 will be driving or operative only during periods when the converter rings are delivering more than 60 cycles. Below 60 cycles the prime mover will be unloaded and the braking effort will be applied by the eddy-current device. Torque is needed at the converter shaft at all frequencies. The power is zero at unity slip or 60 cycles only because the speed is zero. However, there is still a need for a torque effort to be applied to the converter.

The same analysis and derivations can now be applied for a load which is constant torque in nature over the variable-speed range. If the same process is followed as for the fan-type load, a curve can be plotted, as shown in Figure 6.

The four equations relating power flow for a constant-torque load are listed below. The curve characteristics are plotted in terms of per unit ring power and are modified accordingly.

Power stator $= k$

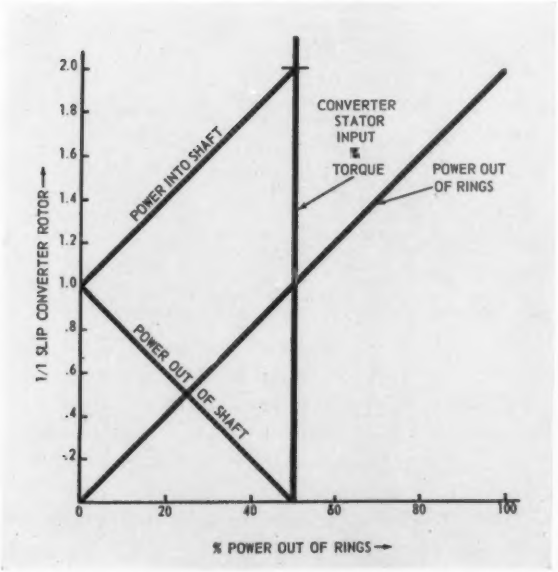
Power rings $= ks$

Power shaft $= k(1-s)$

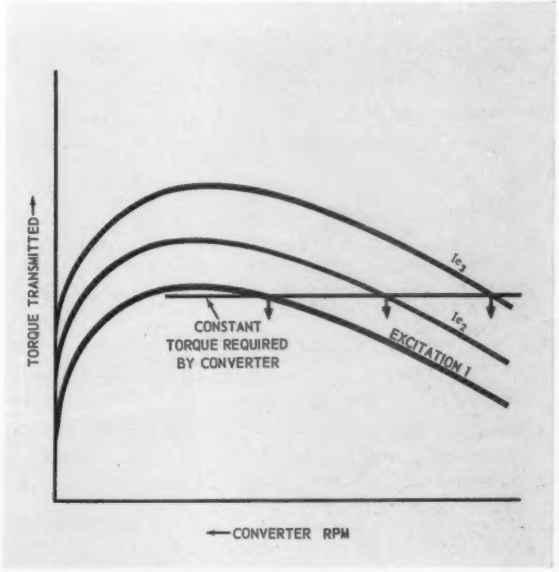
Torque shaft $= k$

In the case of constant-torque ring load the eddy-current device regulates converter speed on the basis of a constant torque required at the converter shaft.

As illustrated in Figure 7, the transmitting capability of the eddy-current device can be varied by changing its ex-



CONVERTER CHARACTERISTICS for a constant-torque load make most efficient use of equipment driving the converter. **(FIGURE 6)**



WITH CONSTANT TORQUE required by the converter rotor, speed is controlled by varying excitation of eddy-current device. **(FIGURE 7)**

citation. Each value of excitation has one transmitting torque characteristic over the rpm range. By adjusting the excitation a given converter speed and ring frequency will be established which in turn will result in the desired cage motor speed.

If a constant horsepower load is applied to the converter rings over the variable-frequency range, the characteristics would be as shown in Figure 8.

The power relationships of the converter for a constant horsepower load are:

$$\text{Power stator} = \frac{k}{s}$$

$$\text{Power rings} = k$$

$$\text{Power shaft} = k\left(\frac{1-s}{s}\right)$$

$$\text{Torque shaft} = \frac{k}{s}$$

Constant horsepower applications require very large machines when operating at low frequencies or with large speed variations.

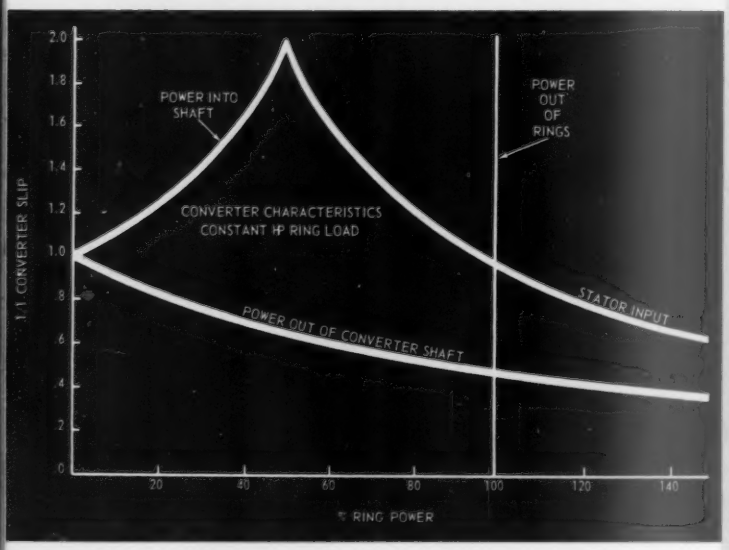
Driving or braking the converter can also be accomplished by variable-voltage equipment. The supporting equipment, whether ac or dc, merely provides regulating power to adjust the drive to its proper frequency.

Feedback control for the ultimate load speed or converter frequency can be obtained by either of two methods.

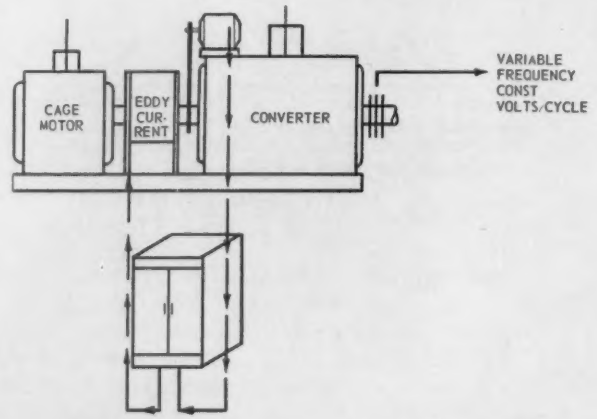
1. A tachometer can be mounted on the converter shaft for measuring speed. The output of this tachometer is fed to the eddy-current control, which in turn will automatically regulate the excitation to the eddy-current device, thus establishing the converter rotor speed. This speed in turn establishes the desired frequency calibrated on the rheostat in the control cubicle.

2. A more elaborate method would be to drive a reluctance-type synchronous motor from the frequency output of the converter. This motor would in turn drive the tachometer, which would provide the feedback signal to the eddy-current control. In this manner frequency is regulated directly. This arrangement has the advantage of regulating for frequency changes in the system connected to the converter armature. Two of the control schematics are shown in Figures 9 and 10.

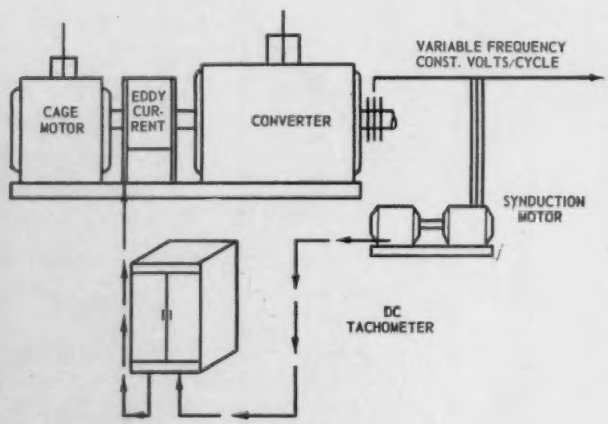
The ac drive system lends itself most readily to variable-speed constant-torque applications. It can also be used in other applications having variable-torque characteristics or for loads having some characteristic between constant torque and variable torque. It is not generally recommended, however, for constant horsepower applications except where speed variations are small.



CONVERTER CHARACTERISTICS for a constant horsepower load result in oversize equipment for low speeds of the load drive motor. **(FIGURE 8)**



FEEDBACK SEQUENCE regulates converter speed. **(FIGURE 9)**



FEEDBACK SEQUENCE regulates converter output frequency. **(FIGURE 10)**

Reduce Sag -- Burndown !

Reduce Annealing

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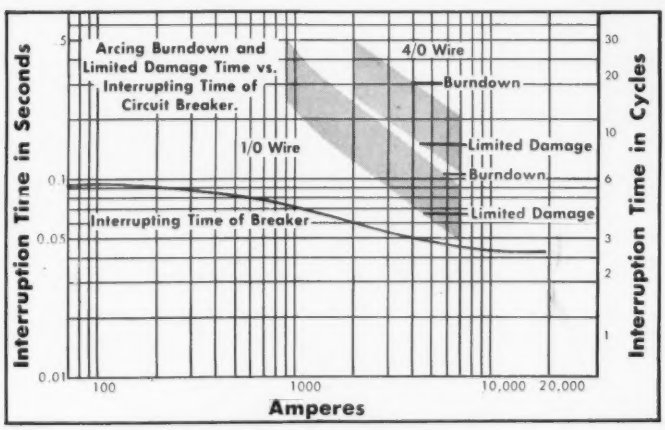
For further details contact your nearby A-C office, or write Allis-Chalmers, Power Equipment Division, Milwaukee 1, Wisconsin.



A commonly used overhead distribution wire is No. 4/0 wire. This curve shows no wire damage occurring when coordinated with this 5 cycle breaker. Notice that interrupting time is well under 5 cycles on heavier currents and is fast on low currents, too.

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